

Hot TOP(phys)ics

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European Research Council
Established by the European Commission

Structure

- Introduction
- Colour Flow
- Angular Distributions
- The Top and The Higgs
- Summary



Introduction

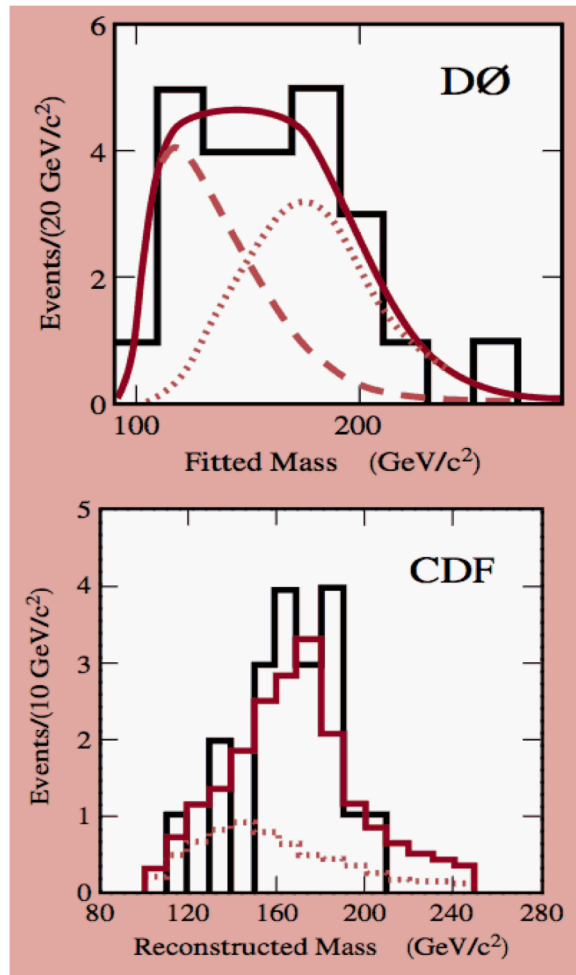
The Top Quark

- Heaviest known elementary particle:
 $m_t \sim 173 \text{ GeV}$
- Standard Model:
 - Single or pair production
 - Electric charge $+2/3 e$
 - Short lifetime $0.5 \times 10^{-24} \text{ s}$
 - Bare quark - no hadronization
 - $\sim 100\%$ decay into Wb
 - Large coupling to SM Higgs boson



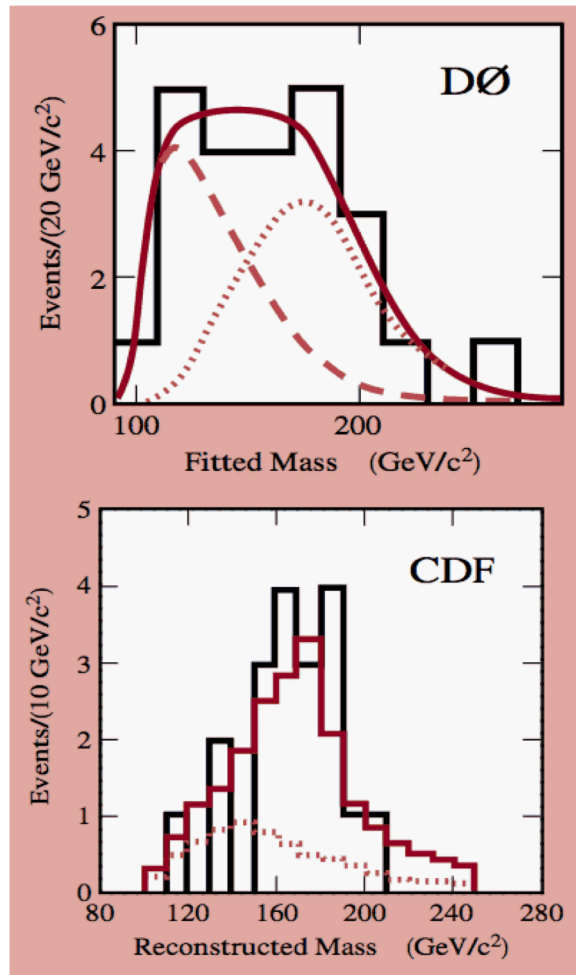
Top: From Discovery...

- Discovered in 1995 by CDF and DØ at Fermilab (with few events)

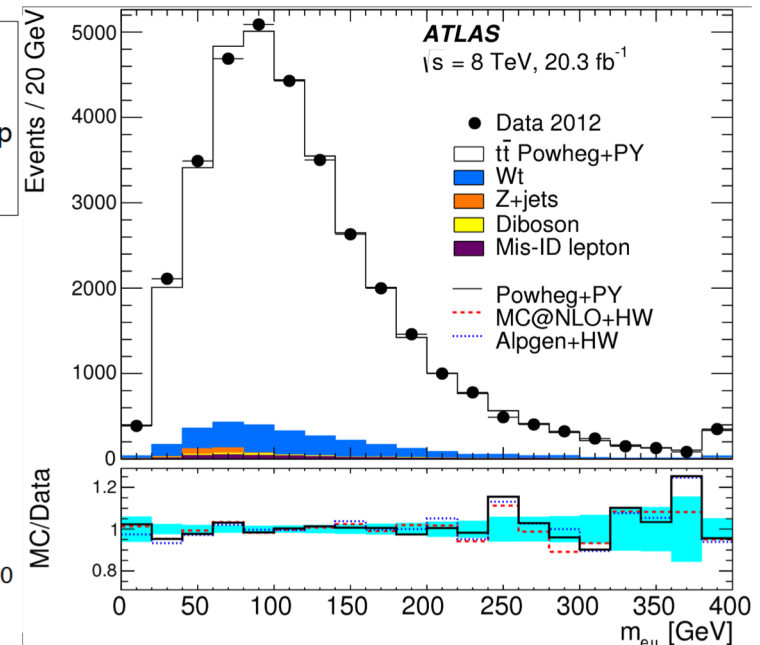
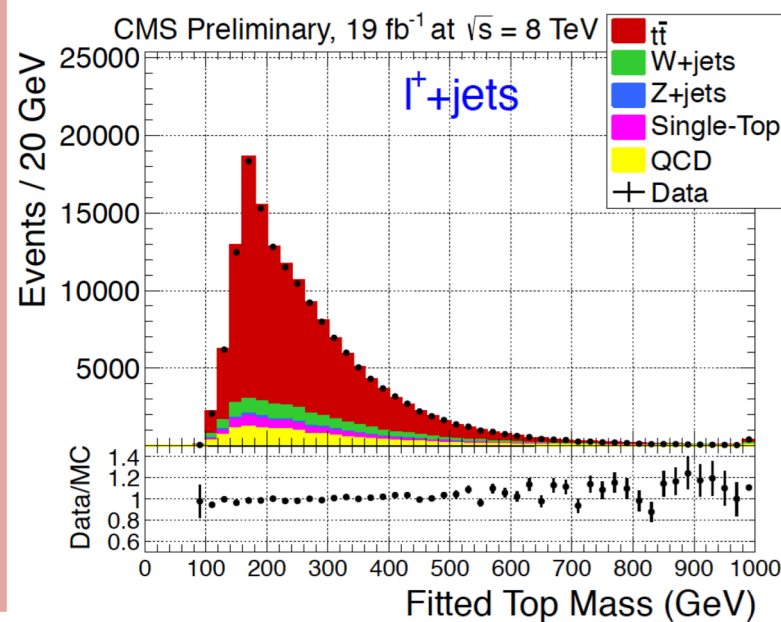


...to Precision

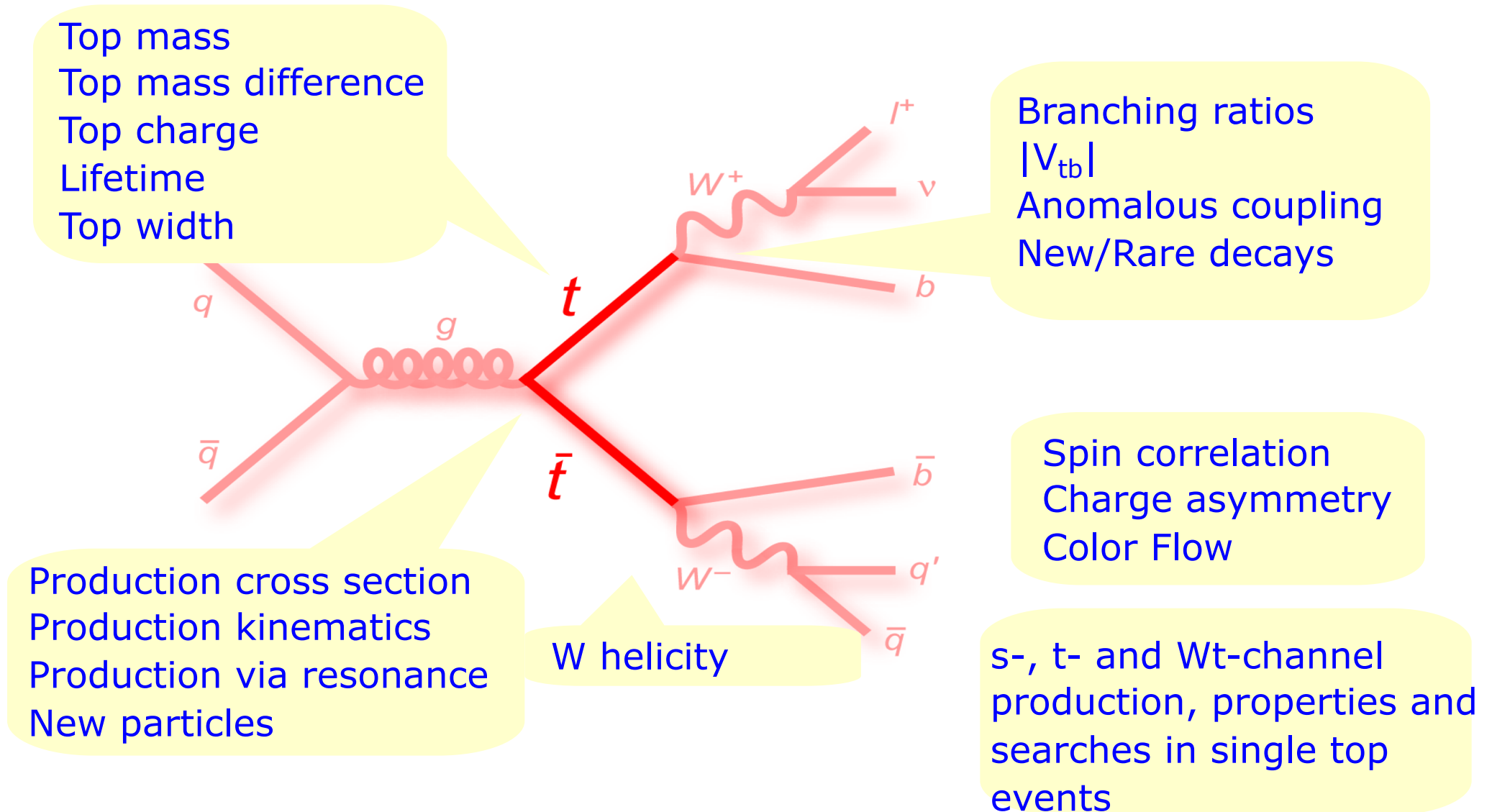
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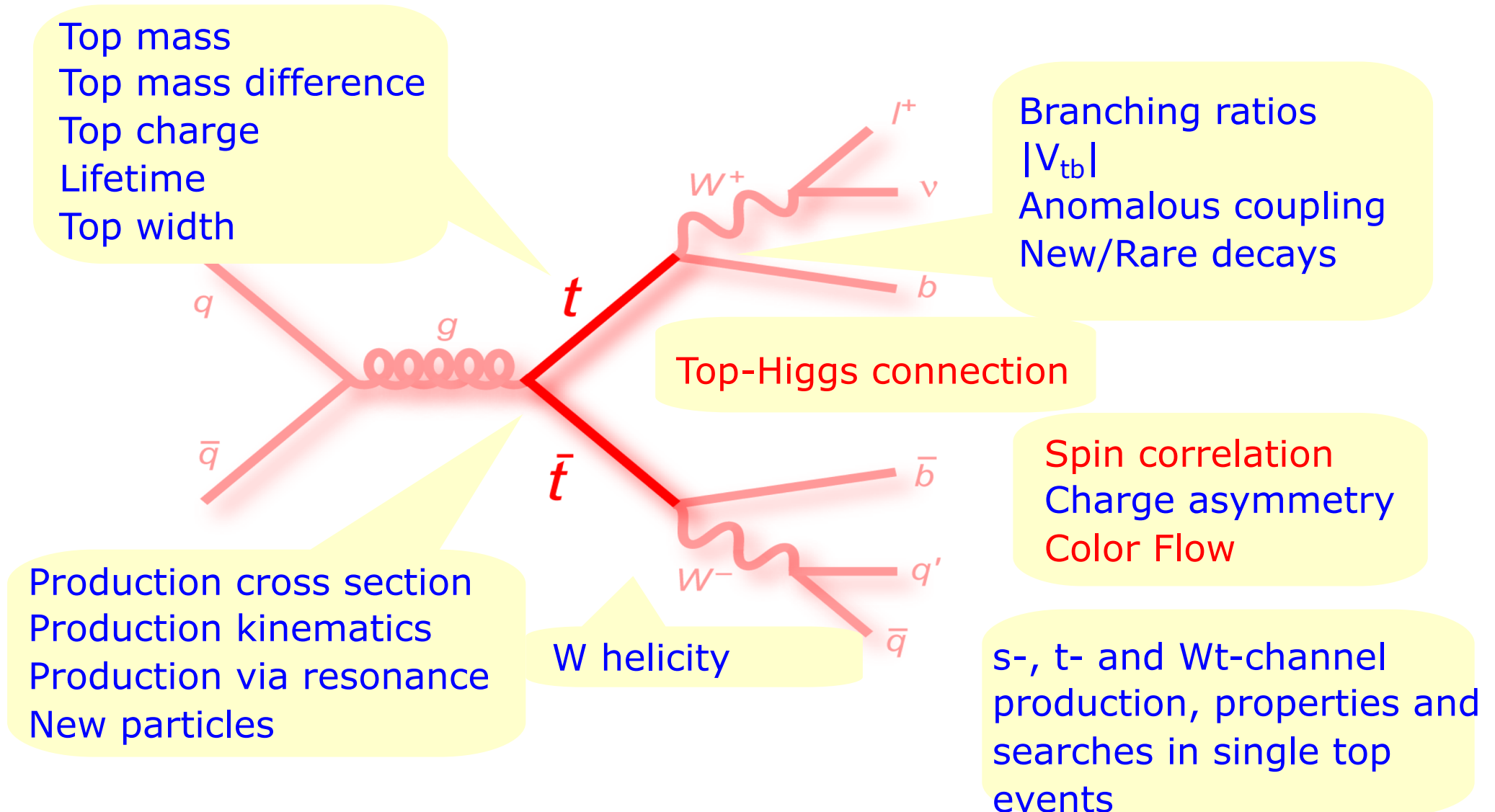
Situation today:
LHC → top quark factory!
Many precision measurements possible!



Top Studies: Overview



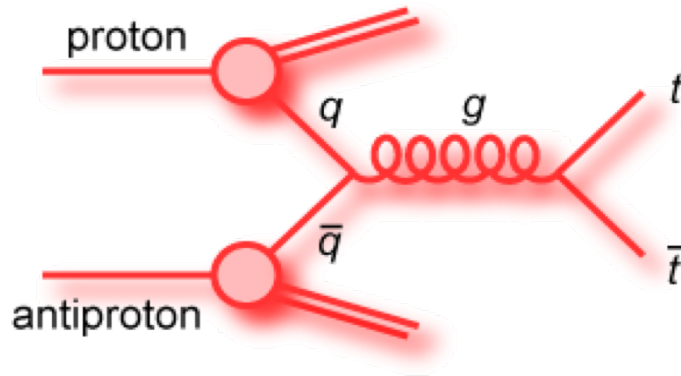
Top Studies: Overview



Top Quark Pair Production

At the Tevatron:

85%



At LHC:

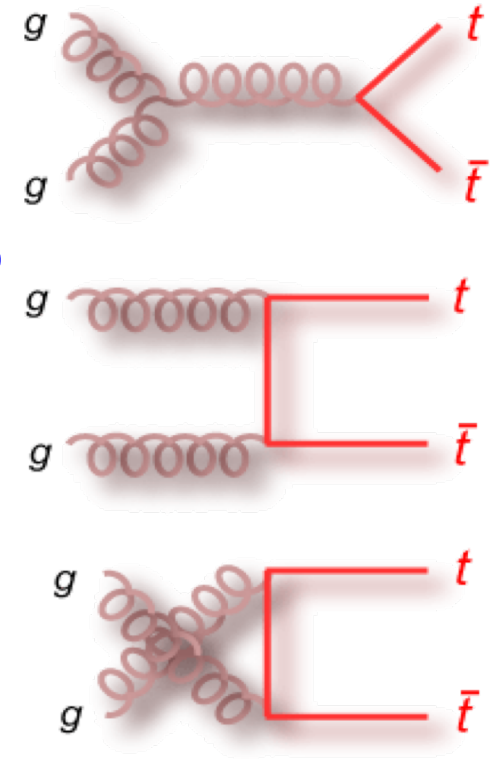
14 TeV: 10%

7 TeV: 30%

+ 15%

+ 90%

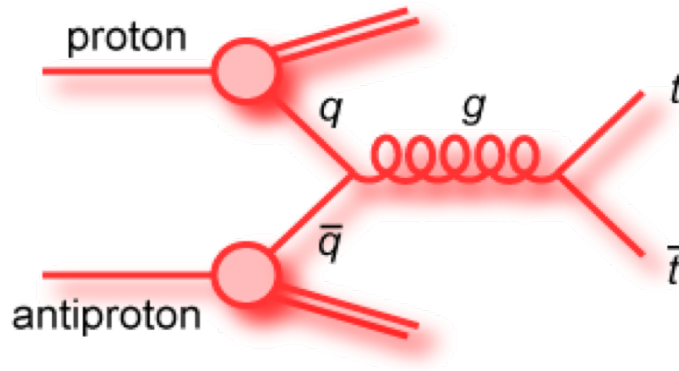
+ 70%



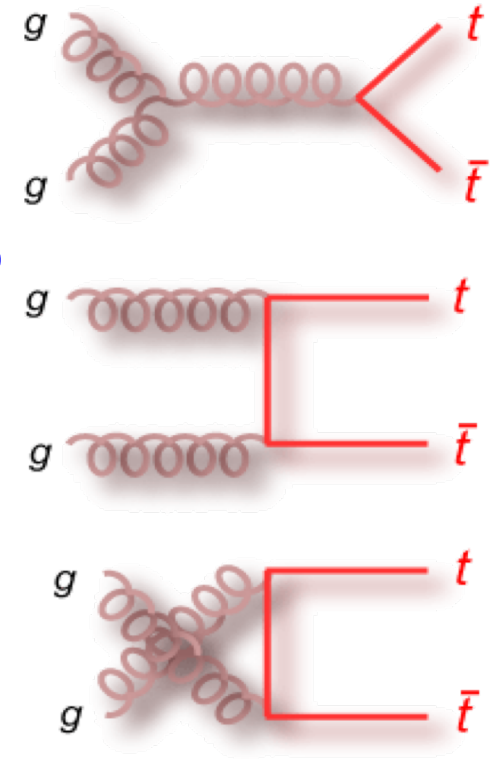
Top Quark Pair Production

At the Tevatron:

85%



+ 15%



At LHC:

14 TeV: 10%

7 TeV: 30%

+ 90%

+ 70%

Cross Sections:

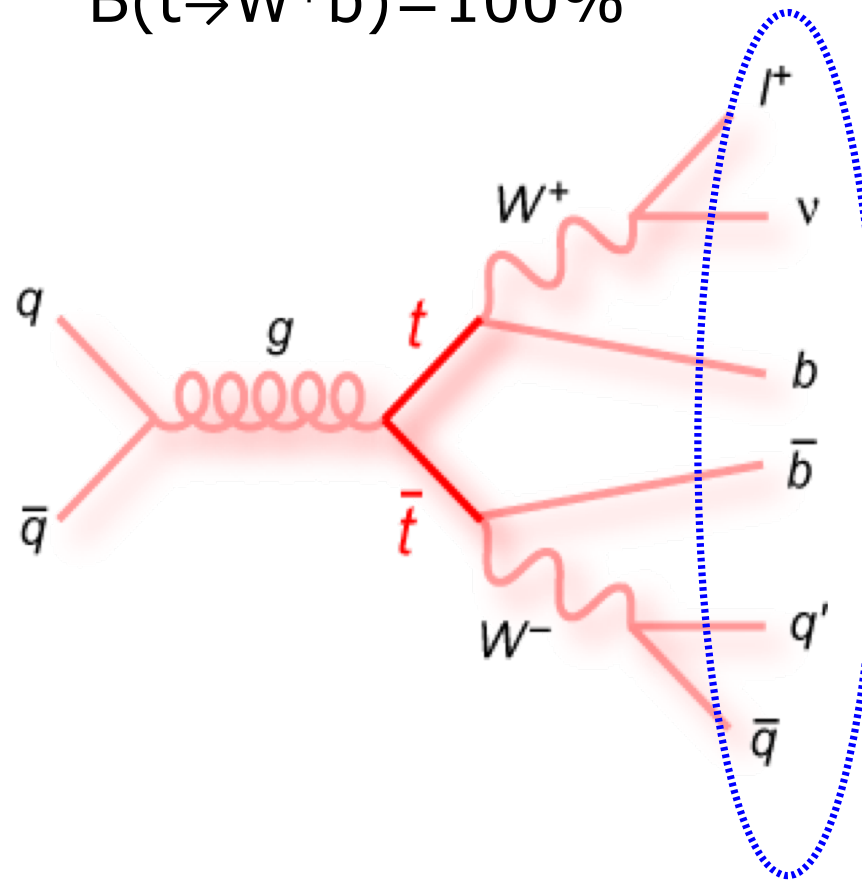
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

M. Czakon et al. arXiv:1112.5675

Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+ b W^- \bar{b}$: Final states are classified according to W decay

$$B(t \rightarrow W^+ b) = 100\%$$



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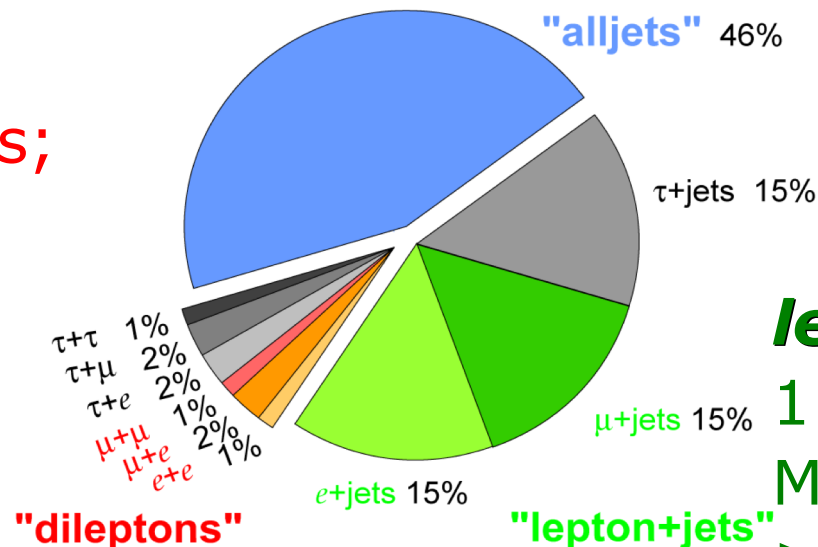
$$B(t \rightarrow W^+ b) = 100\%$$

Top Pair Branching Fractions

all-hadronic:
 ≥ 6 jets (2 b-jets)

dilepton:

2 isolated leptons;
High missing E_T
from neutrinos;
2 b-jets

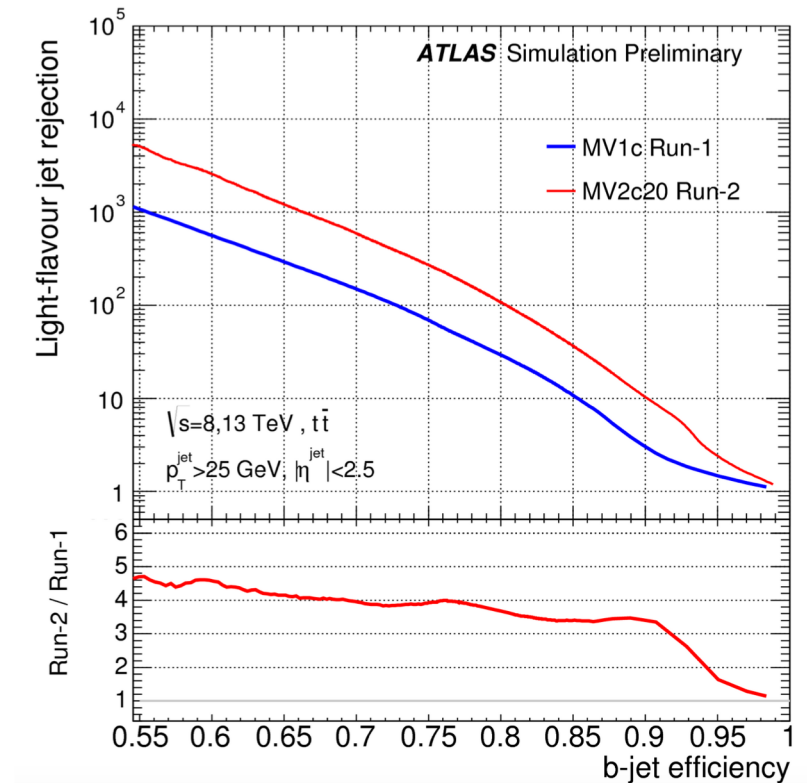
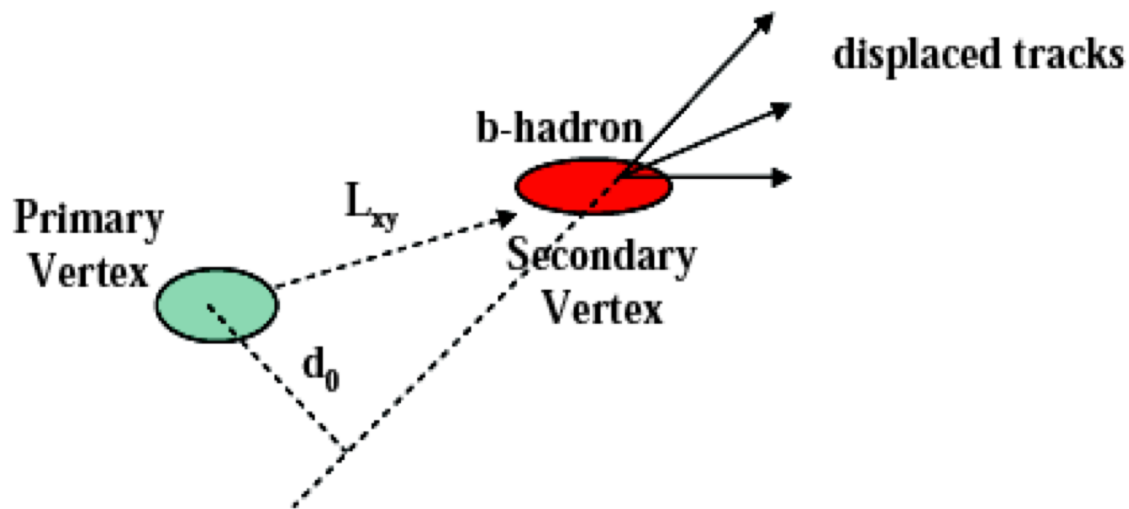


lepton+jets:

1 isolated lepton;
Missing E_T from neutrino;
 ≥ 4 jets (2 b-jets)

Ideontification of b-Jets

- Important tool to increase $t\bar{t}$ purity
- **b-hadron**: travels some millimeters before it decays
- **Neural Network** (MV1)
combines properties of displaced tracks and displaced vertices



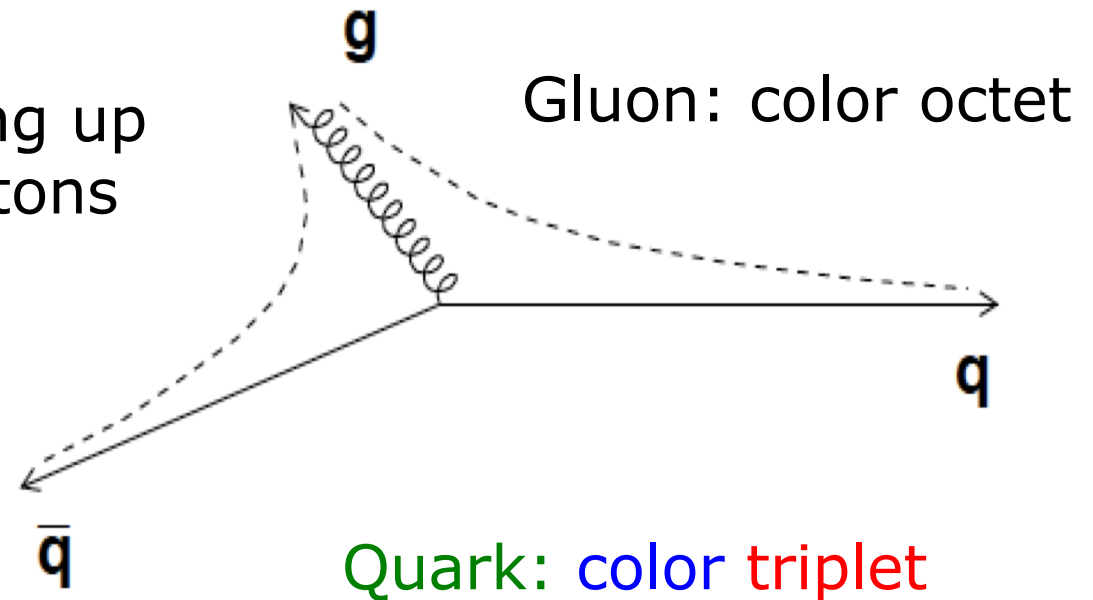
ATLAS-PHYS-PUB-2015-022



Top Events as a Laboratory

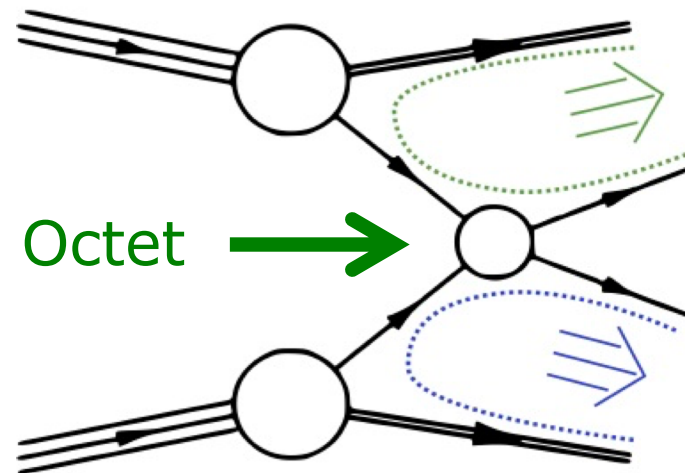
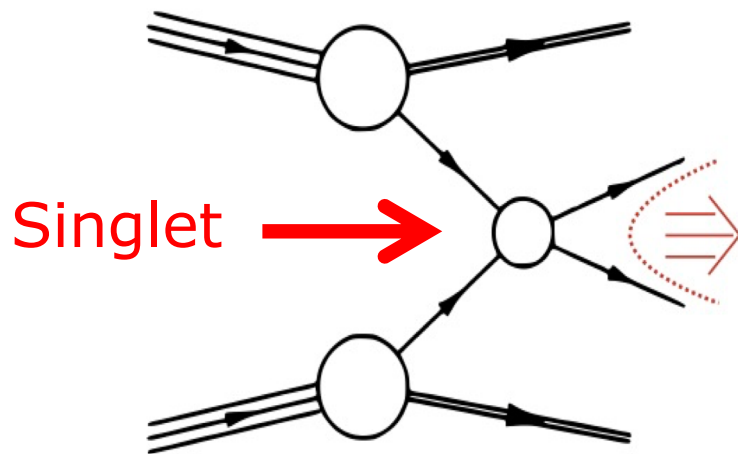
Introduction to Colour Connection and Hadronization

- Quarks carry QCD color charge
 - But only colour singlets can be observed
 - For example W, Z, or bound states like hadrons
- Partons carrying color are **color connected** to partons with anti-colour
- **Hadronization**: Particles building up between colour-connected partons



Color Flow between Jets

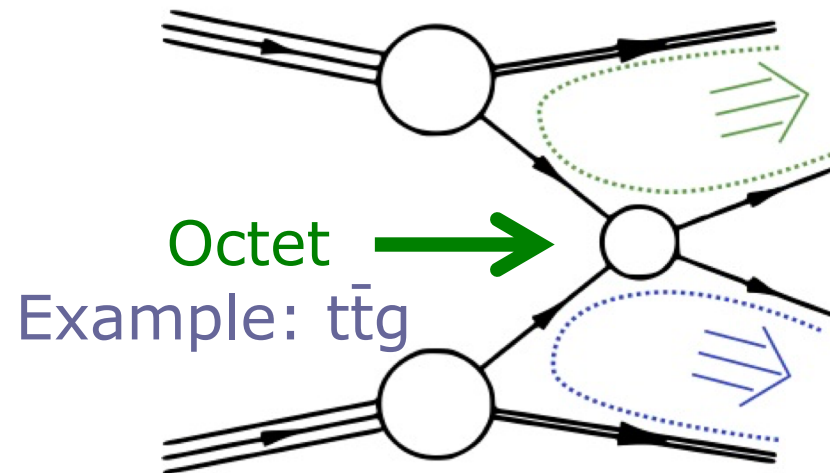
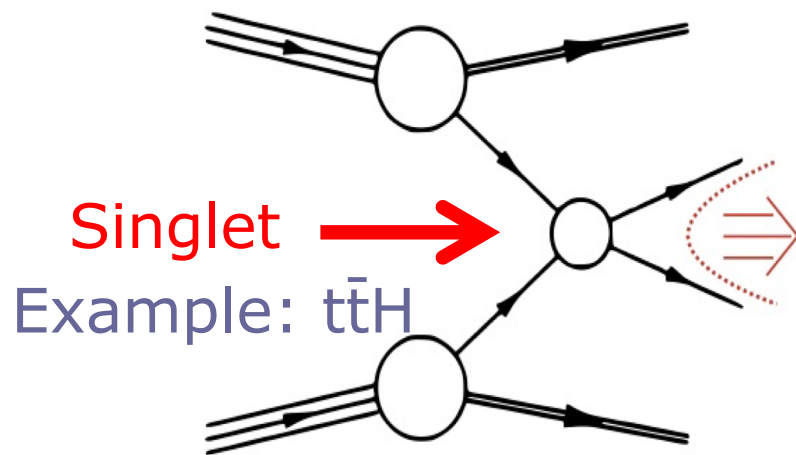
- Jets carry color, and are thus **color connected** to each other
 - Pairing of connection depends on nature of decaying particles



- Particles created during hadronization should be concentrated along angular region spanned by the color connected partons
 - Transverse jet profiles should not be round
 - Shape influenced by direction of color flow!

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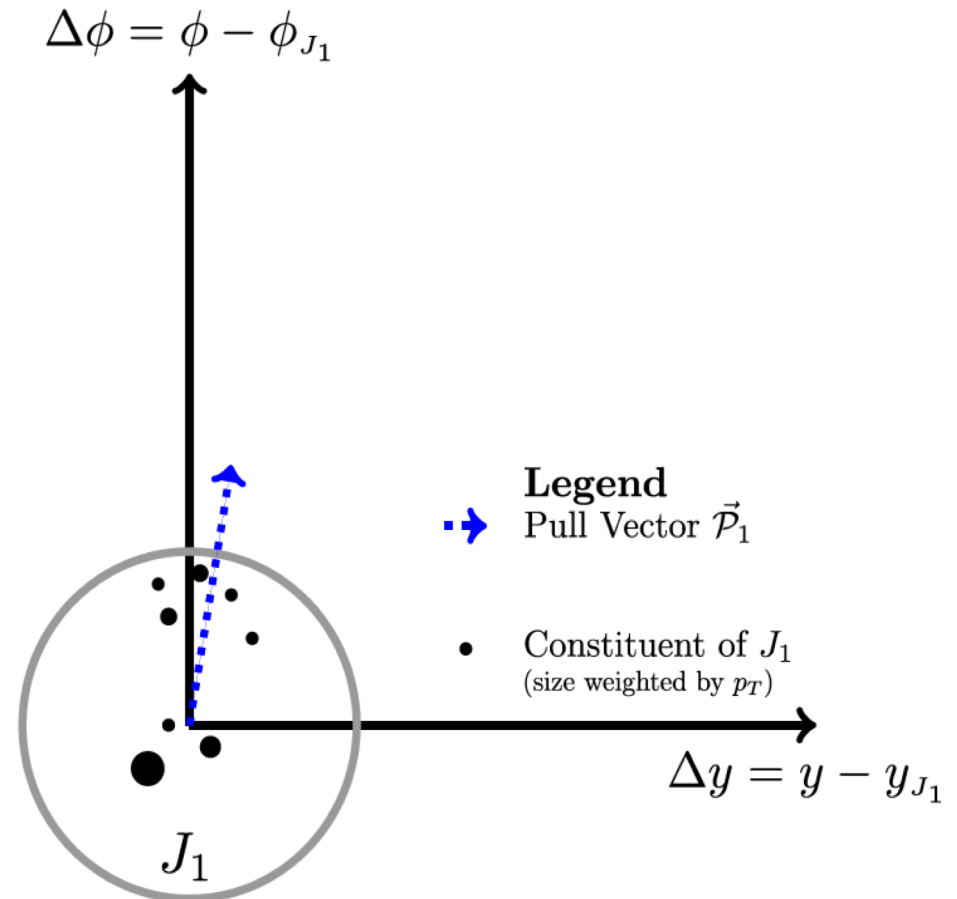
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Color Flow Observable

- Construct a local observable, constructed from particles within a chosen jet cone: **Jet pull**
- Pick a pair of jets in the event
- Build vectorial sum of jet components:

$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$

- $\vec{r}_i$: position of jet component i relative to center of jet
- E_T^i : transverse energy of component i
- E_T^{jet} : transverse energy of jet



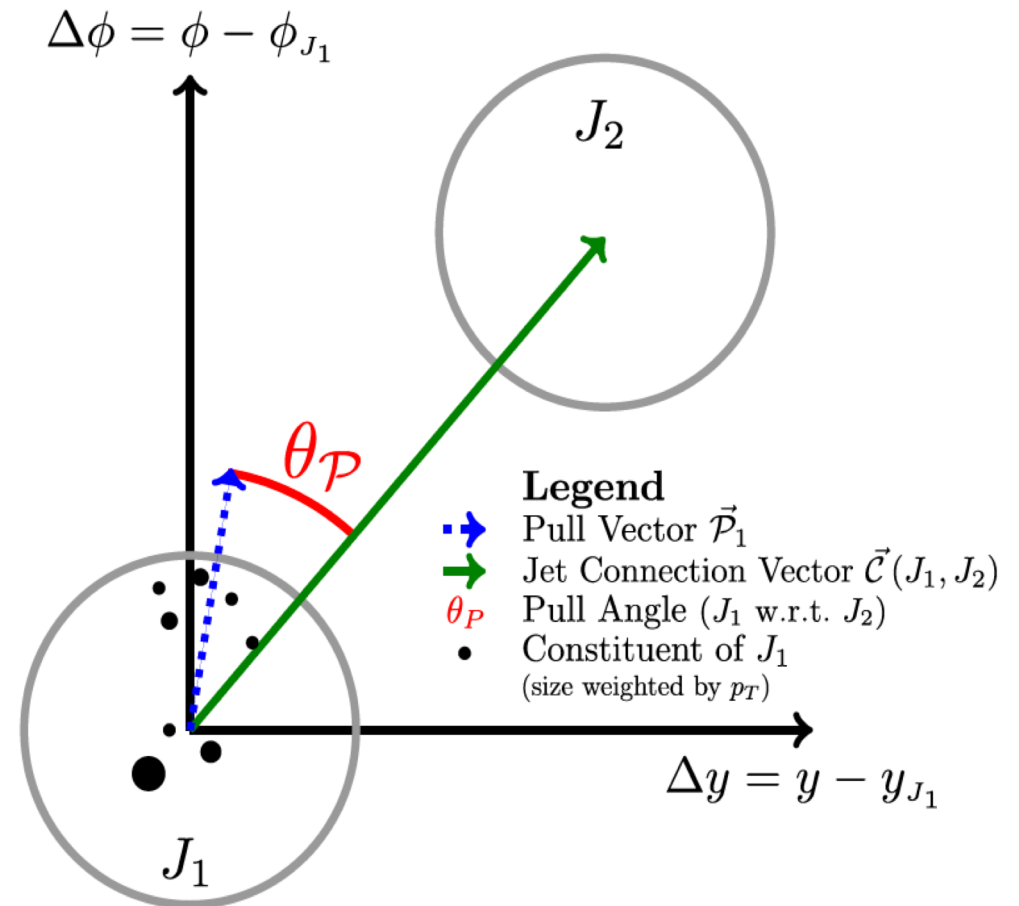
Gallicchio, Schwartz,
PRL 105, 022001 (2010)

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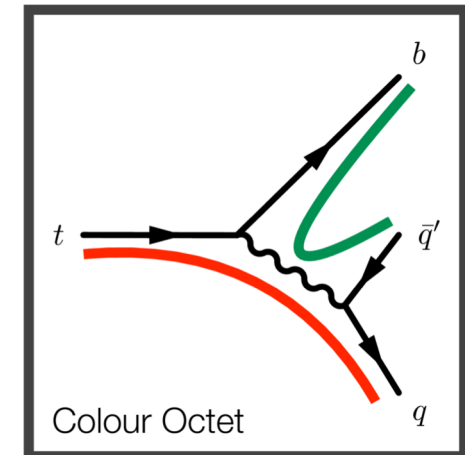
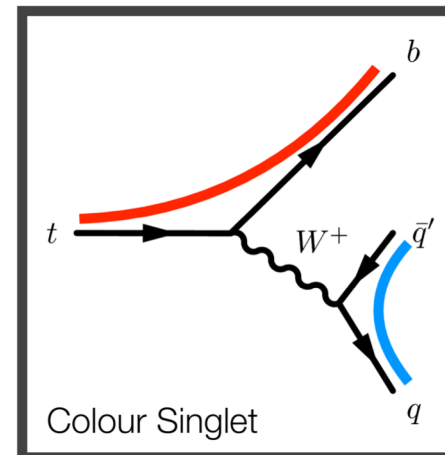


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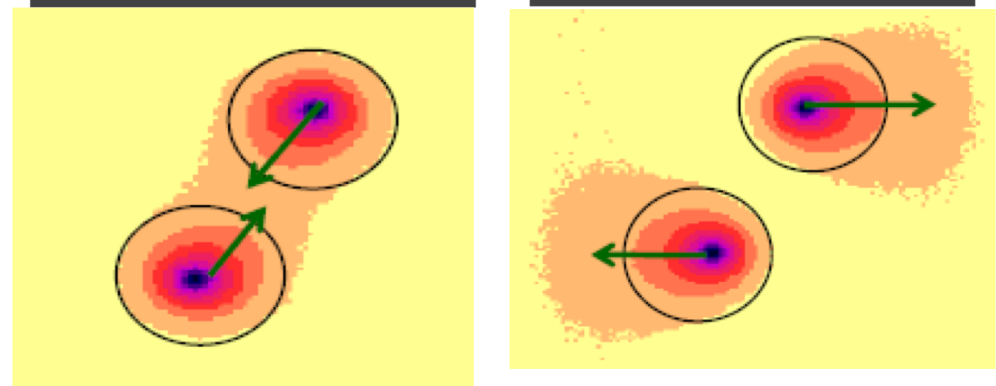
Colour Flow in Top

- Top events as laboratory to test new tools
- Jets carry color, and are thus **color connected** to each other
 - Pairing of connection depends on nature of decaying particles

Gallichio, Schwartz,
PRL 105, 022001 (2010)



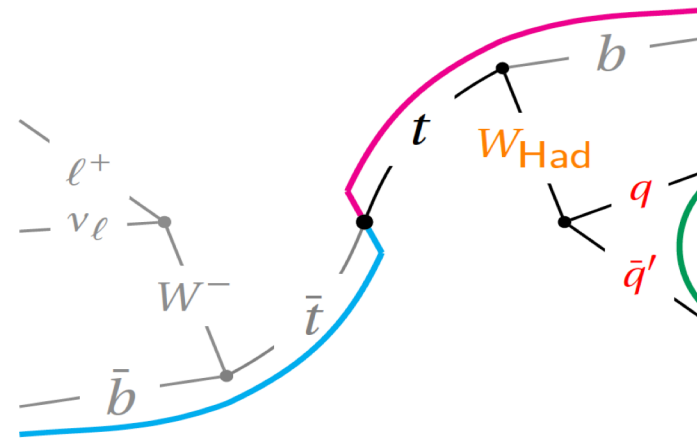
Jet pull: vectorial sum of components within each jet
 → **jet pull angle**: angle wrt. connection line of pair of jets



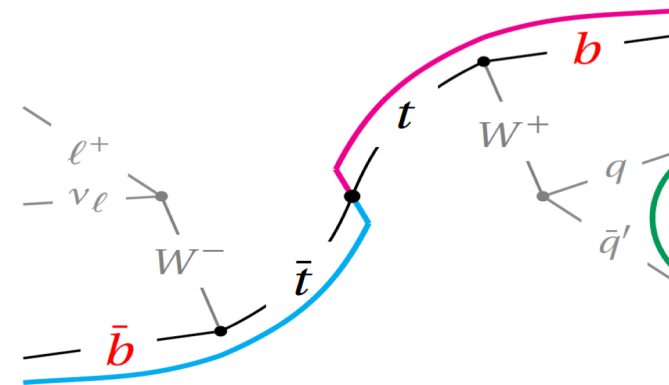
Colour Flow in Top

- Consider 4 variables in semileptonic $t\bar{t}$ events (>1 b-tagged jet)

- Two non-b-tagged jets:
 - Relative jet pull angles
 - Jet pull magnitude

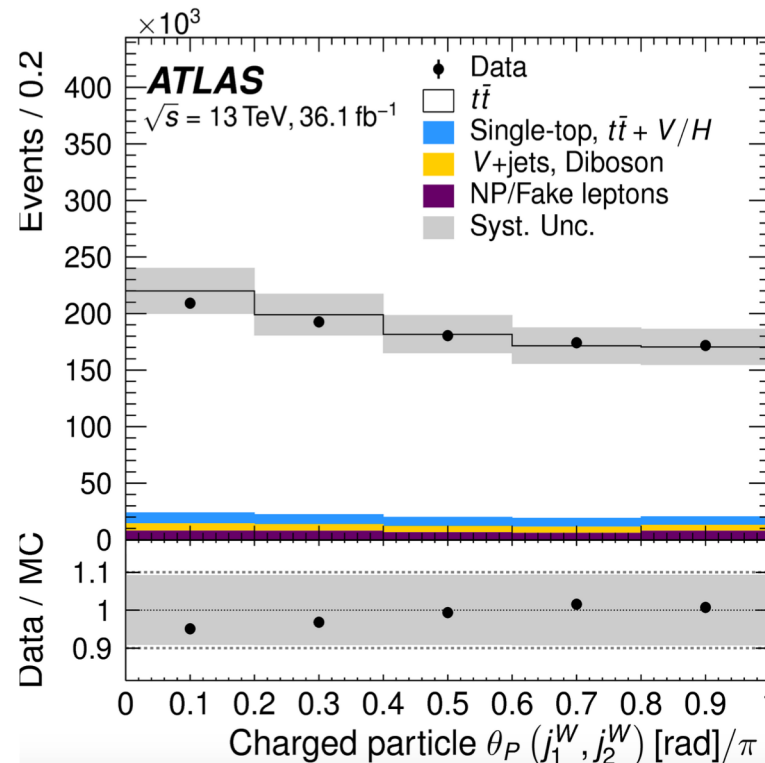


- Two b-tagged jets
 - Relative jet pull angle



Analysis

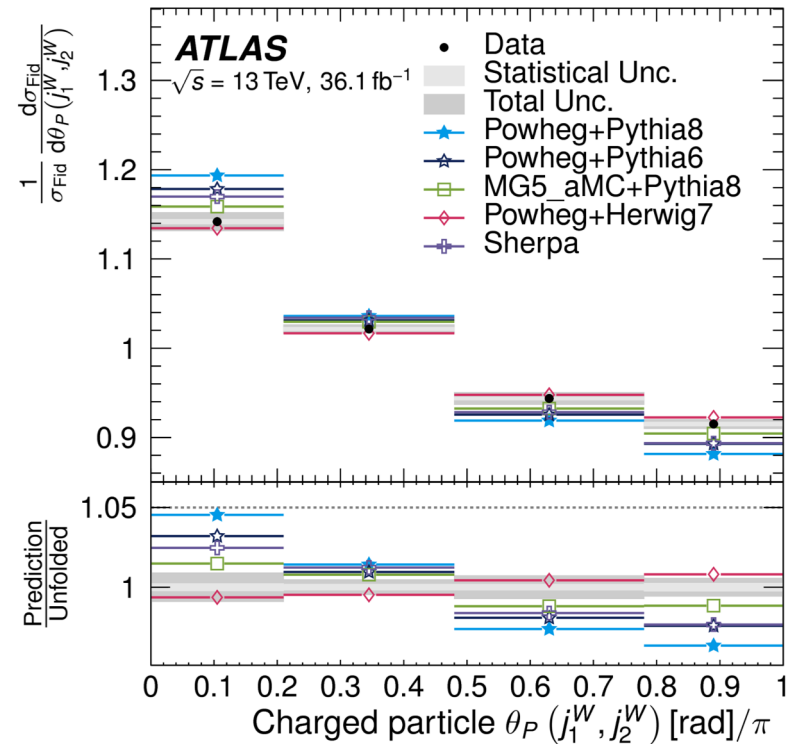
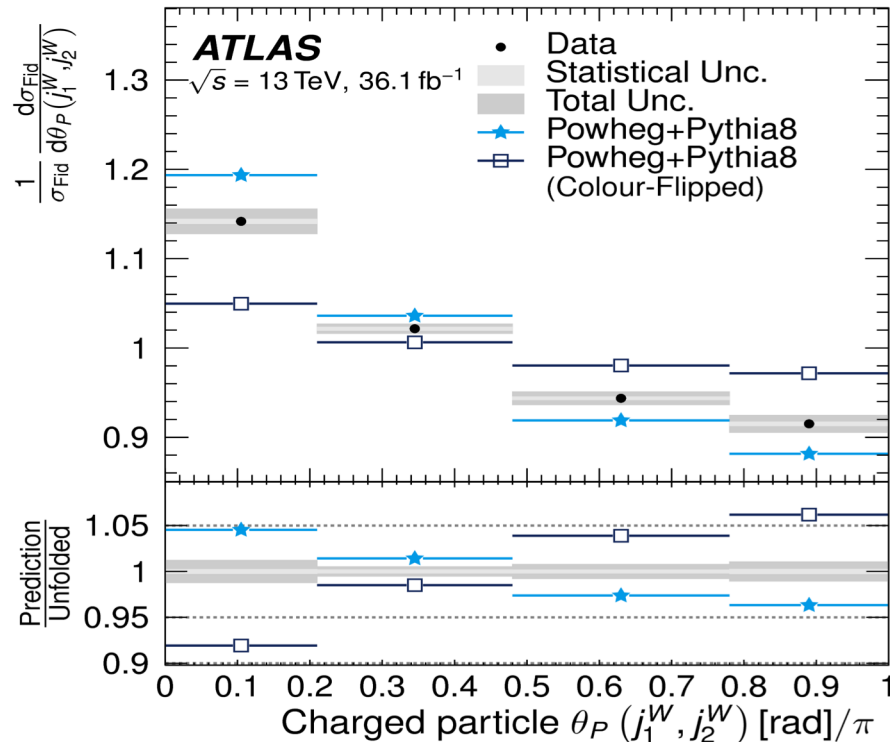
- Correct distributions for detector effects
- 13 TeV analysis: use only track-jets
 - Have shown to have better resolution than calorimeter jets in 8 TeV analysis [PLB 750, 475-493 \(2015\)](#)



[Eur. Phys. J. C 78 \(2018\) 847](#)

Results for W Daughters

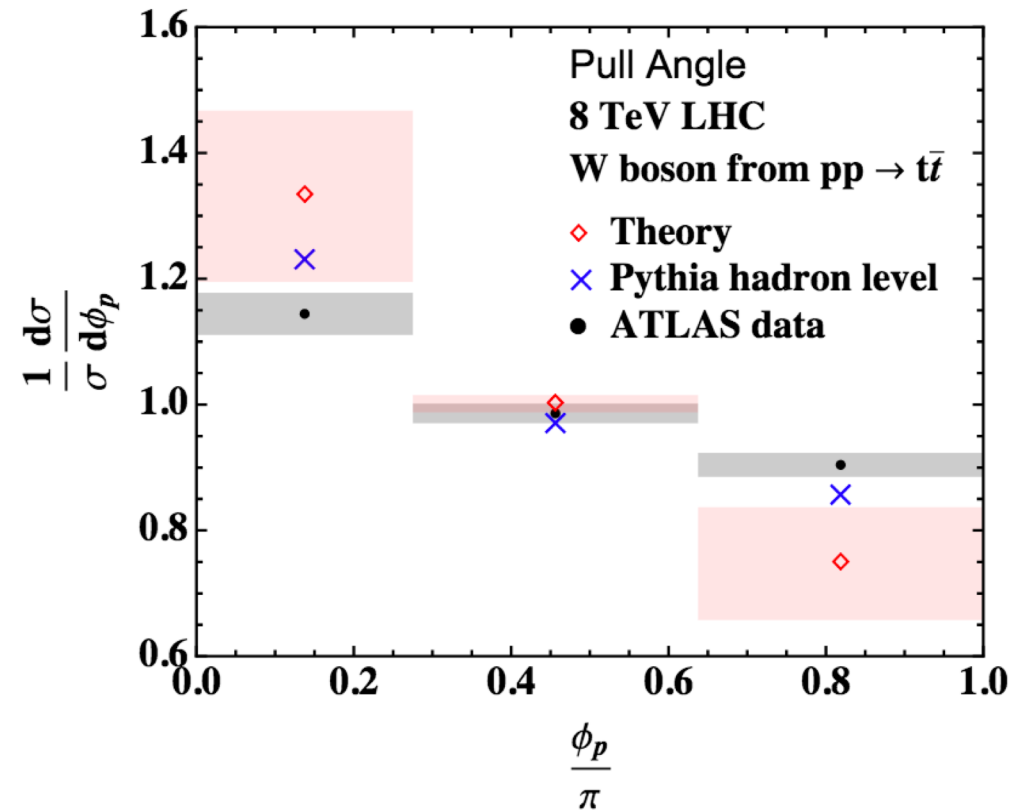
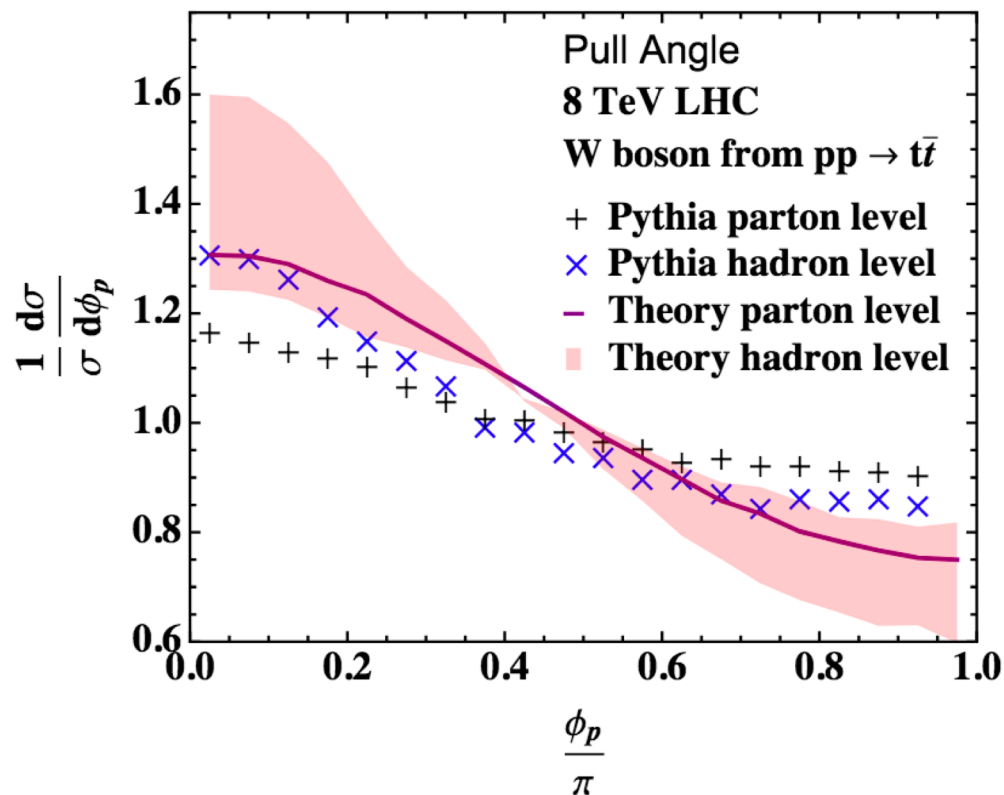
- Correction to stable particle-level (iterative Bayesian unfolding)



- Colour-flipped model disfavoured by the data
(for this distribution χ^2/NDF : 45.3/3; SM Powheg+Pythia8: 17.1/3)
- MC modeling has room for improvement

Theory

- Recent theory paper on theory prediction for Pull Angle
 - In house here in Genova – I better shut up and let the experts explain ;)



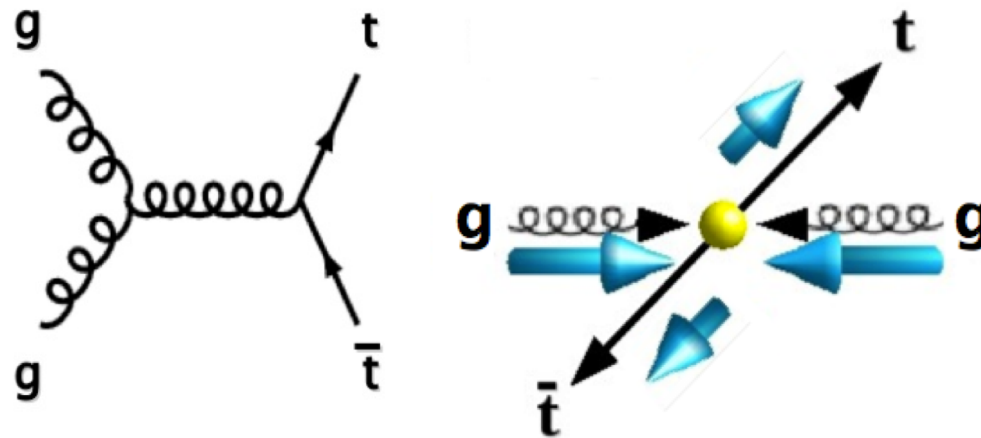
- First theoretical predictions of pull

[arXiv:1903.02275](https://arxiv.org/abs/1903.02275)

Angular Distributions

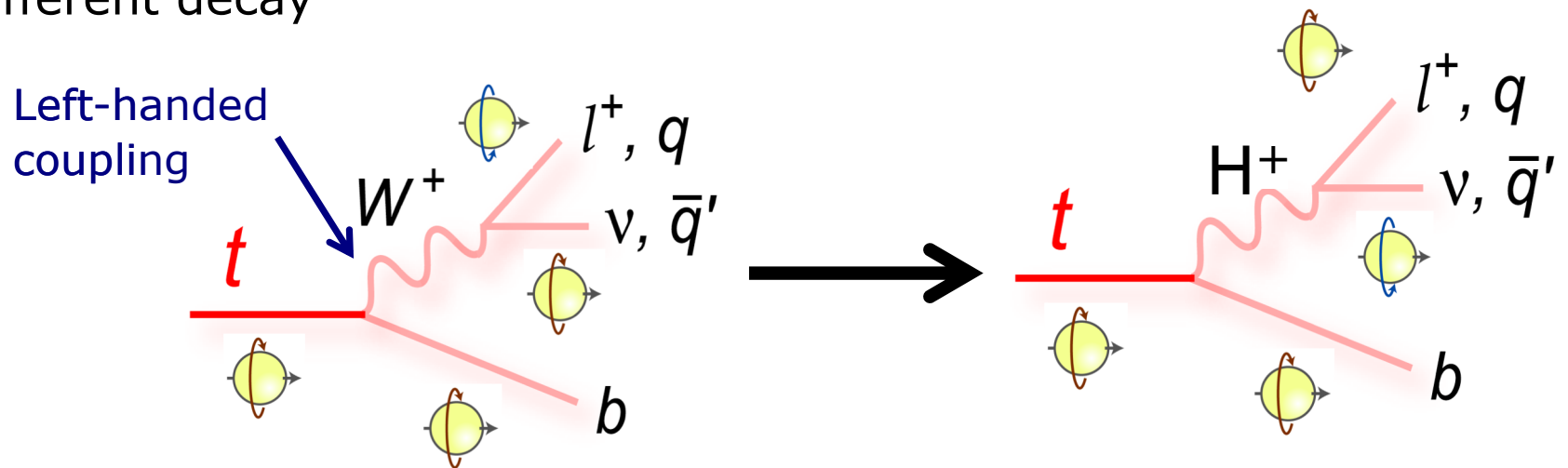
Spin Correlations

- Top quarks: decay before fragmentation
 - Spin information preserved in decay products
- Hadron colliders: top quarks produced unpolarized, but
 - New physics could induce polarization
 - For example: new physics can cause forward-backward asymmetry
→ more left-handed top quarks
 - Correlation between top and antitop quark can be measured

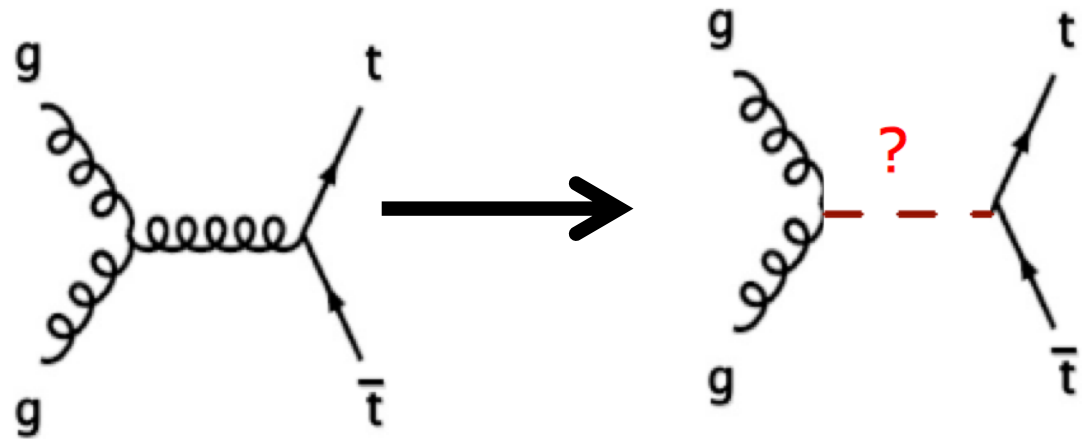


Spin Correlations

- Measured spin correlation can change
 - Due to different decay



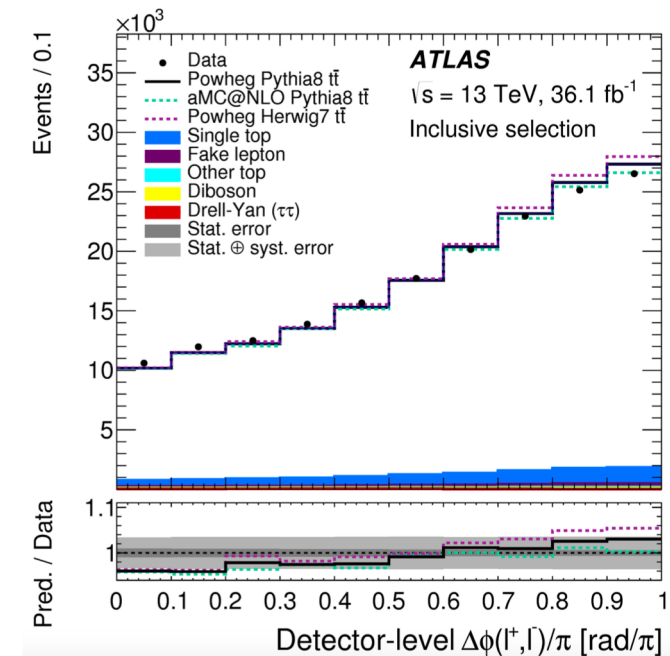
- Due to different production



- Spin correlation: **test full chain from production to decay**

Analysis Strategy

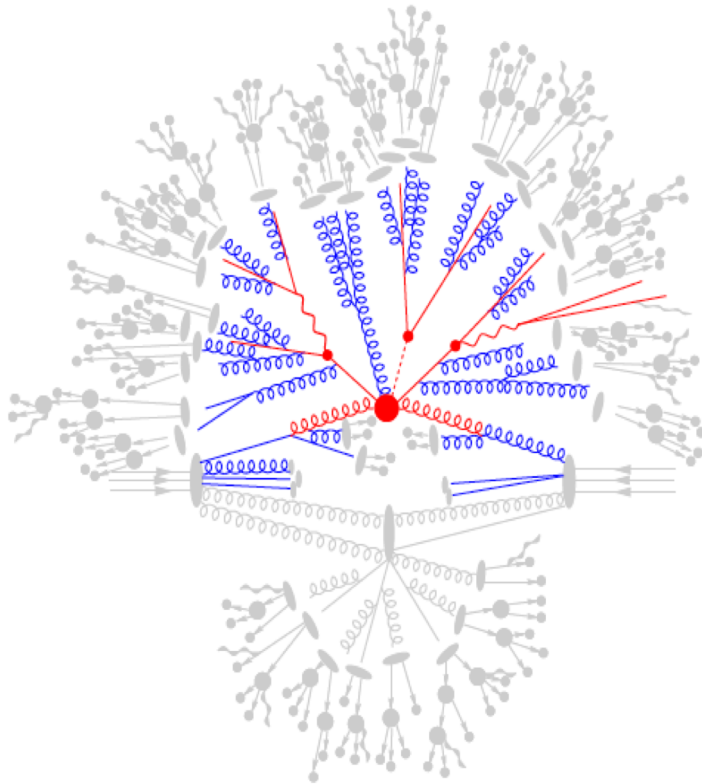
- Highest spin analyzing power: leptons from top decay
 - Use dileptonic $t\bar{t}$ events
 - Very clean samples
- Use $\Delta\varphi$ between both leptons
 - No kinematic event reconstruction required
- Full $t\bar{t}$ event reconstruction for $m_{t\bar{t}}$
 - For example neutrino weighting in ATLAS
 - Uses known top and W boson mass as constraints to explore missing neutrino information



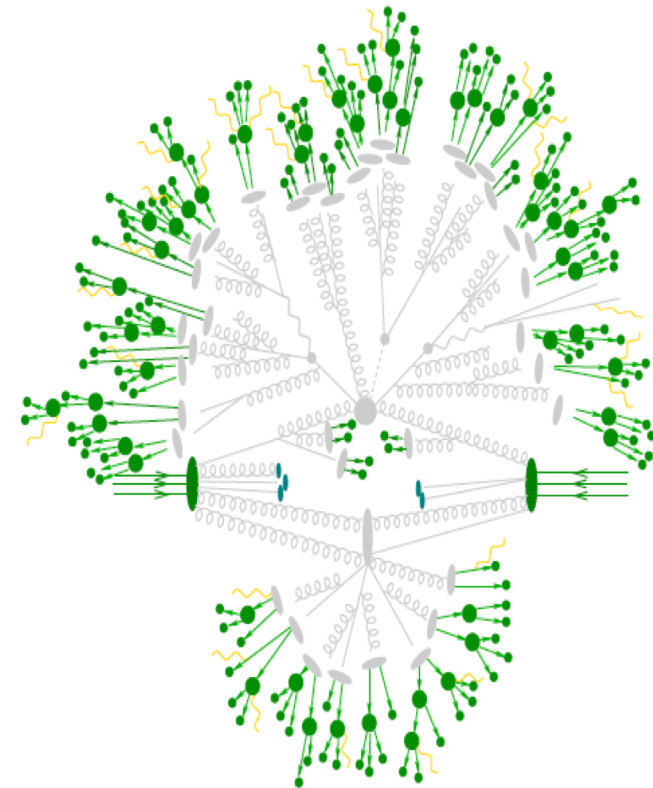
[arxiv:1903.07570](https://arxiv.org/abs/1903.07570)

Analysis Strategy

- Unfolded differential measurements:
Parton-level

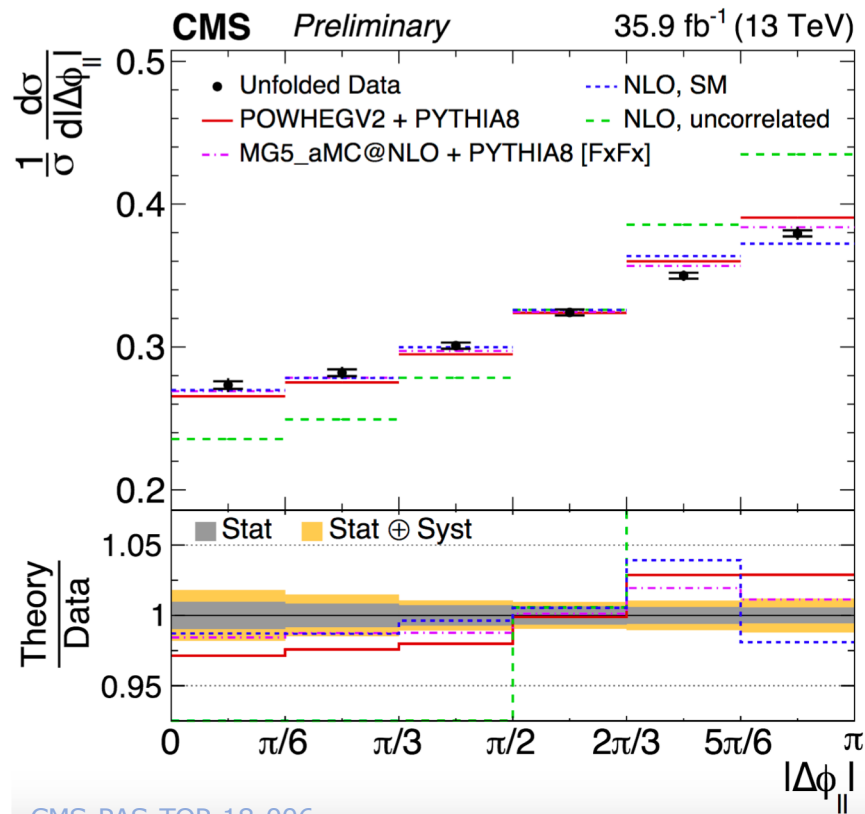


Particle level

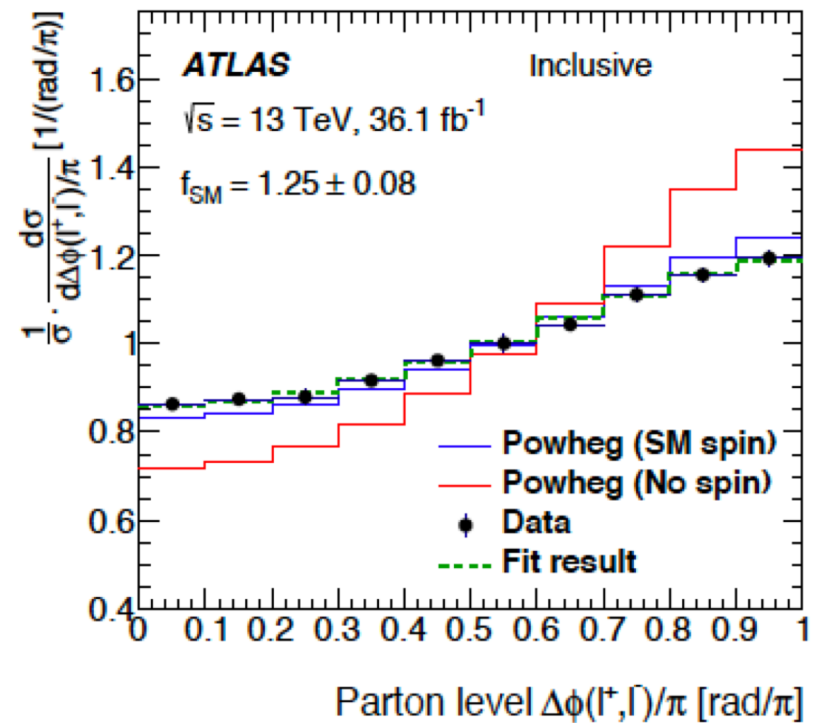


Measured Distributions

- Both ATLAS & CMS: **fitted spin correlation higher than expected**
 - ATLAS: 3.2σ from SM prediction of Powheg MC



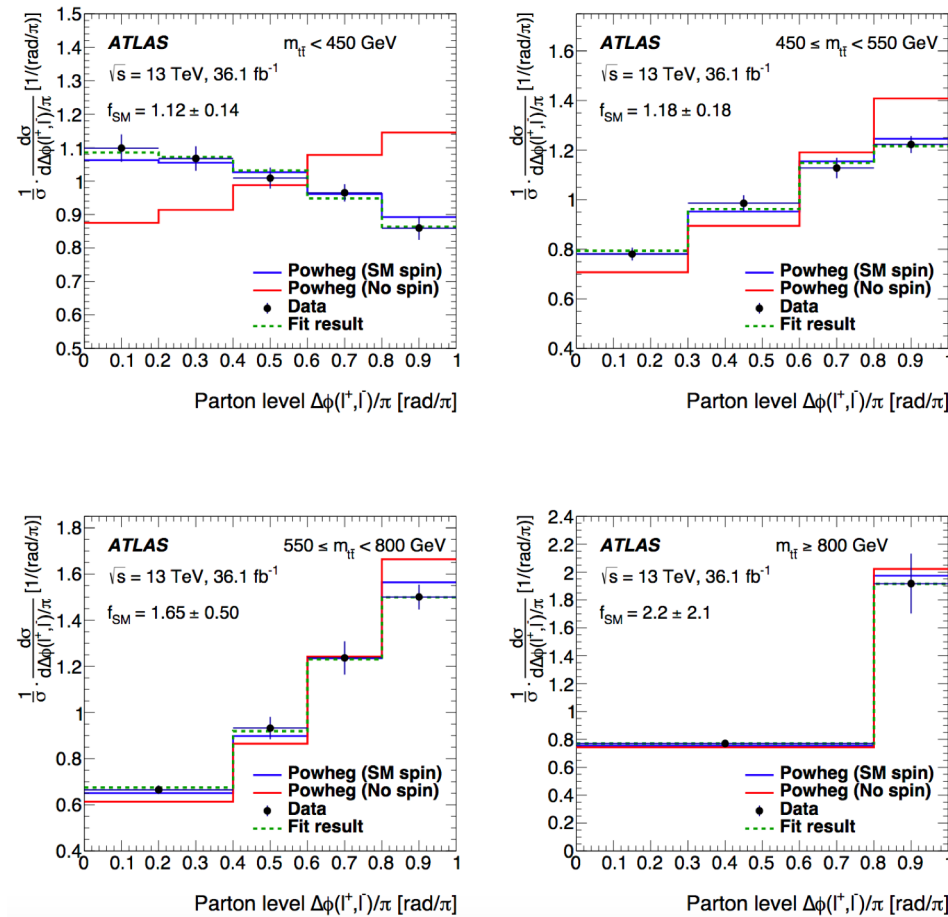
CMS-PAS-TOP-18-006



arxiv:1903.07570

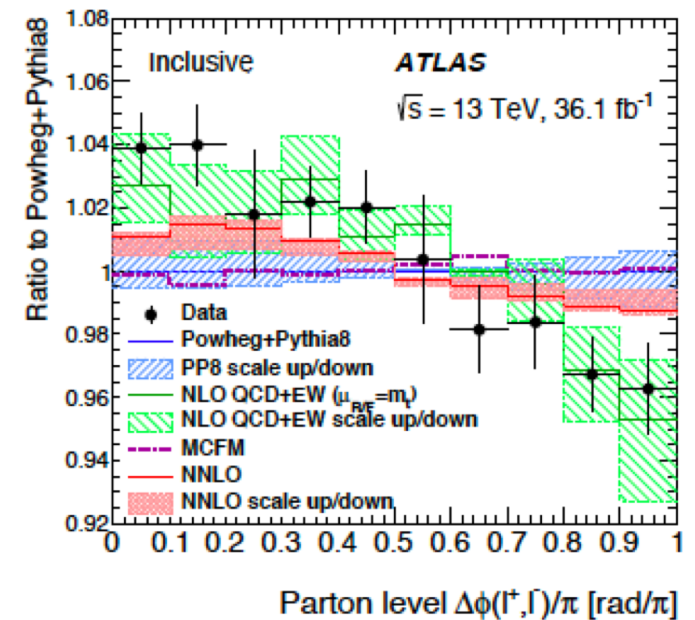
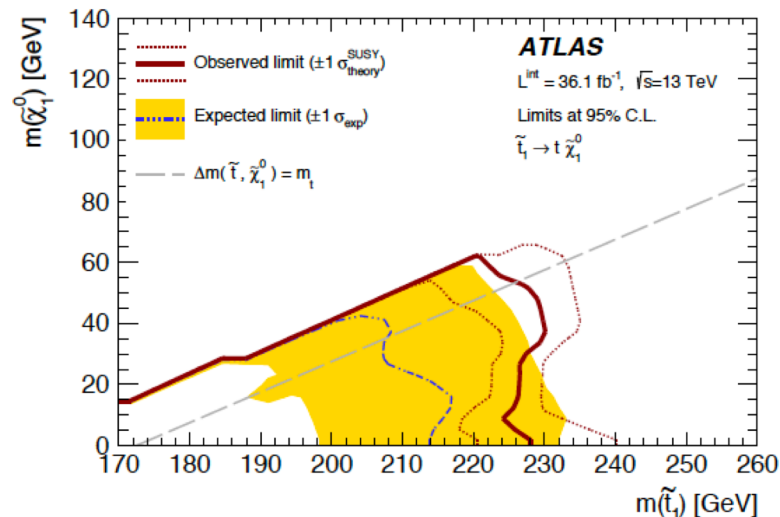
Template Fit

- Fitting spin and no-spin hypotheses to parton-level distributions



More measured distributions

- Result caused interest in field → **new theory predictions**
- NLO+EW agrees better with measurement, NNLO (but no EW corrections) worse again
 - NLO+EW: large scale uncertainties
 - Still open riddle what's exactly going on!
 - Need more calculations/measurements?
- Interpretations done in terms of EFT and SuSy models



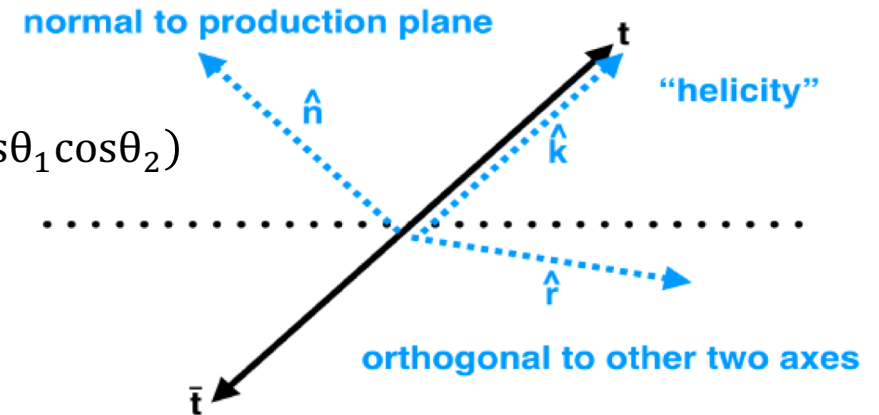
arxiv:1903.07570

Other Measurements

- Double differential cross section:

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} (1 \pm (\alpha P)_1 \cos\theta_1 \pm (\alpha P)_2 \cos\theta_2 - C \cos\theta_1 \cos\theta_2)$$

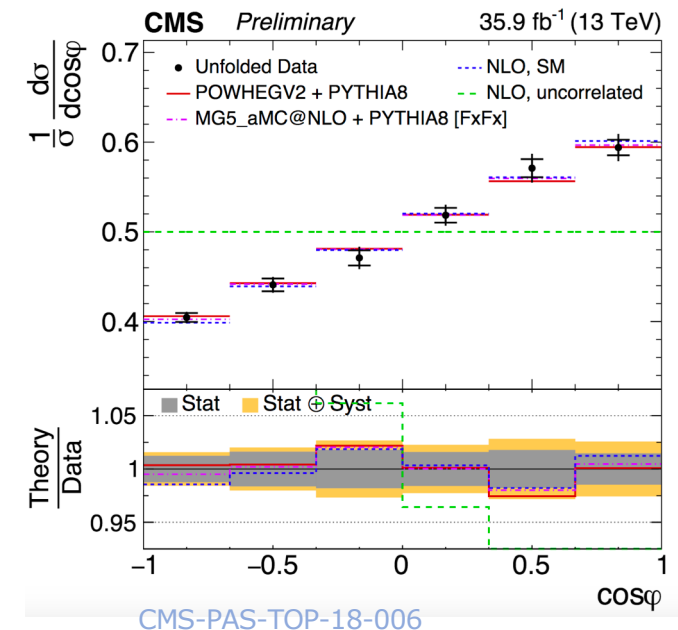
- α : spin analyzing power of decay product
- θ : direction of daughter particle wrt. chosen quantization axis
- P: polarization and C: spin correlations



- More “direct” spin correlation measurement:
Spin density matrix elements

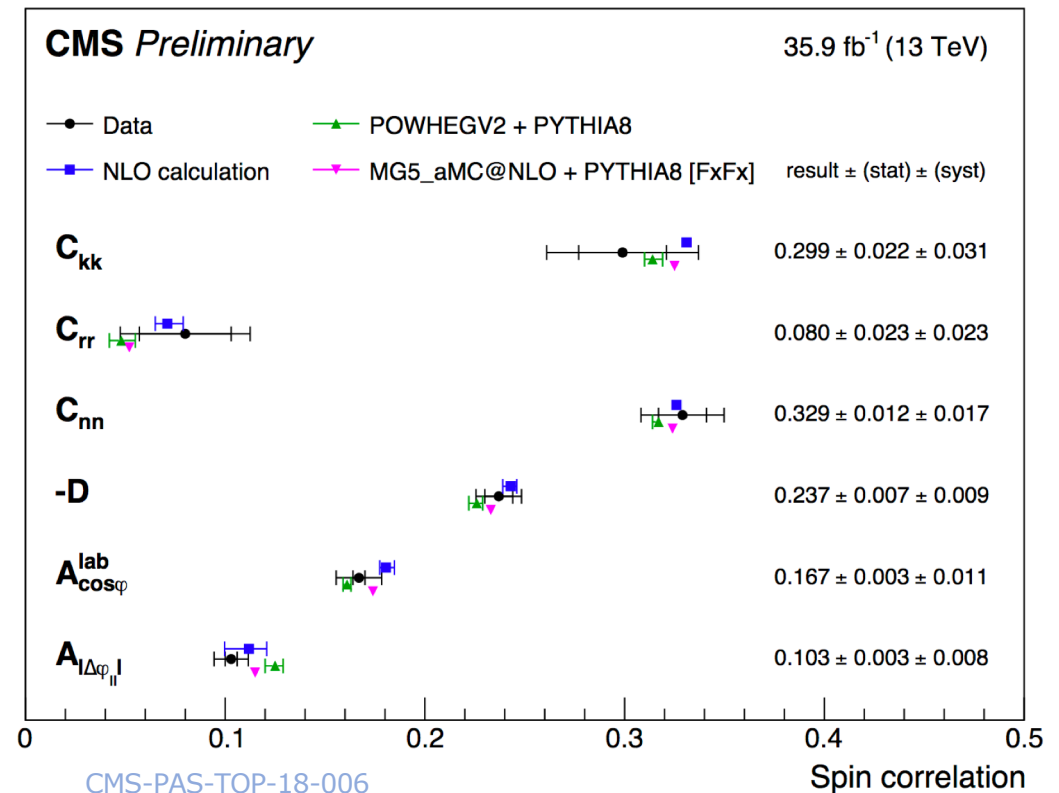
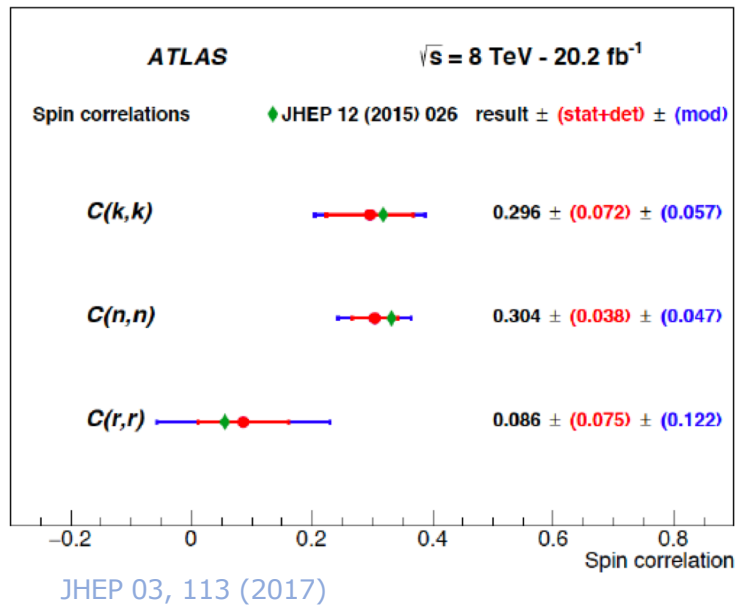
- Challenge: requires full event reconstruction

- ATLAS & CMS:
Unfolded distributions extracted



Other Spin Measurements

- All spin-density matrix elements measured
 - More to do to improve sensitivity

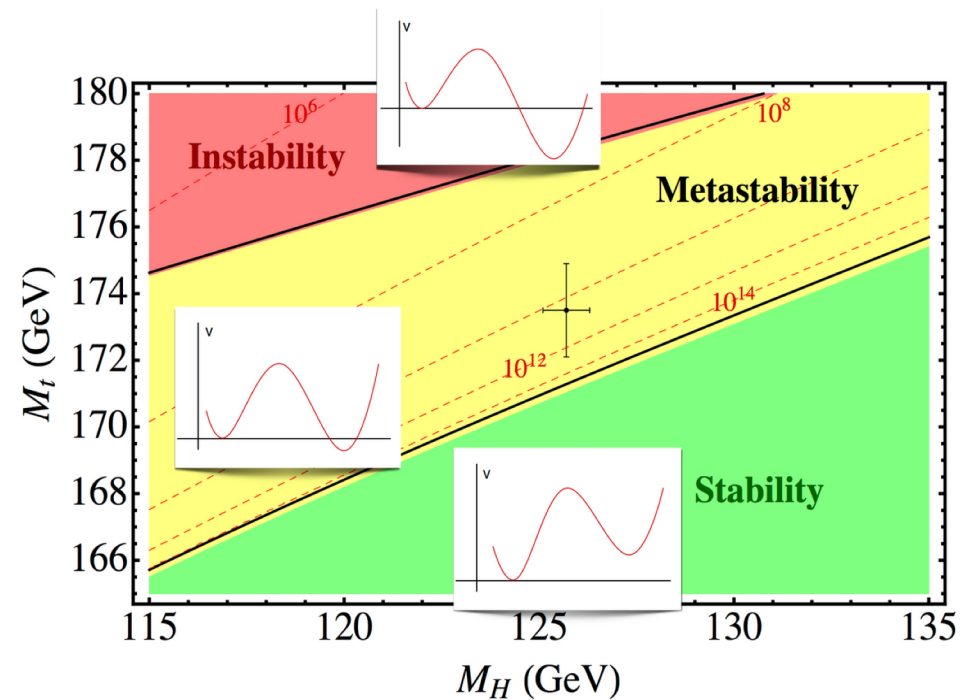
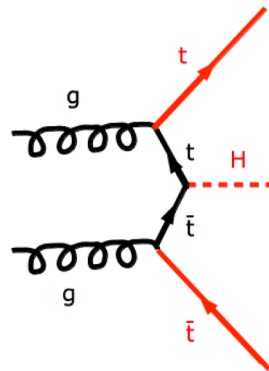


- Still more to do to understand the riddle of $t\bar{t}$ spin correlations!

The Top and The Higgs

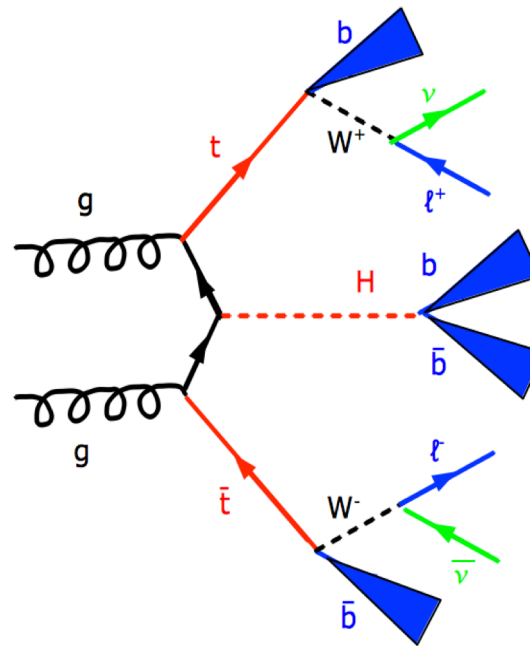
The Top and The Higgs

- Top and Higgs: **Heaviest known elementary fermion and boson!**
 - Top-Higgs Yukawa** coupling:
predicted to be ~ 1 in the SM
→ special role of top quark in electroweak symmetry breaking?
→ window to new physics?
→ metastable universe?
- Measuring top-Higgs Yukawa coupling **directly**: important!
(indirectly: in $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$)
 - Main channel: $t\bar{t}H$



The Top and The Higgs

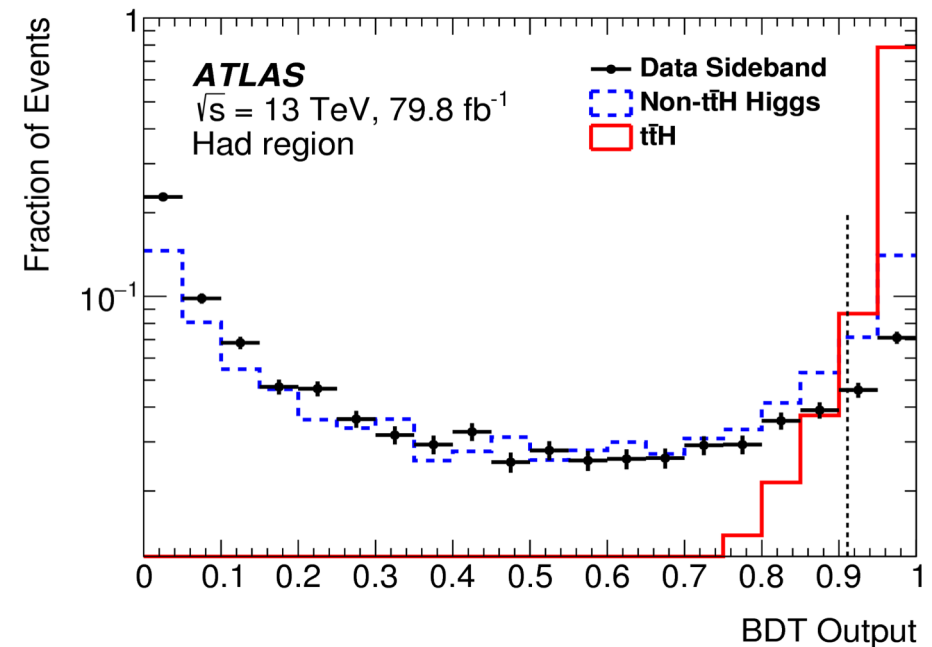
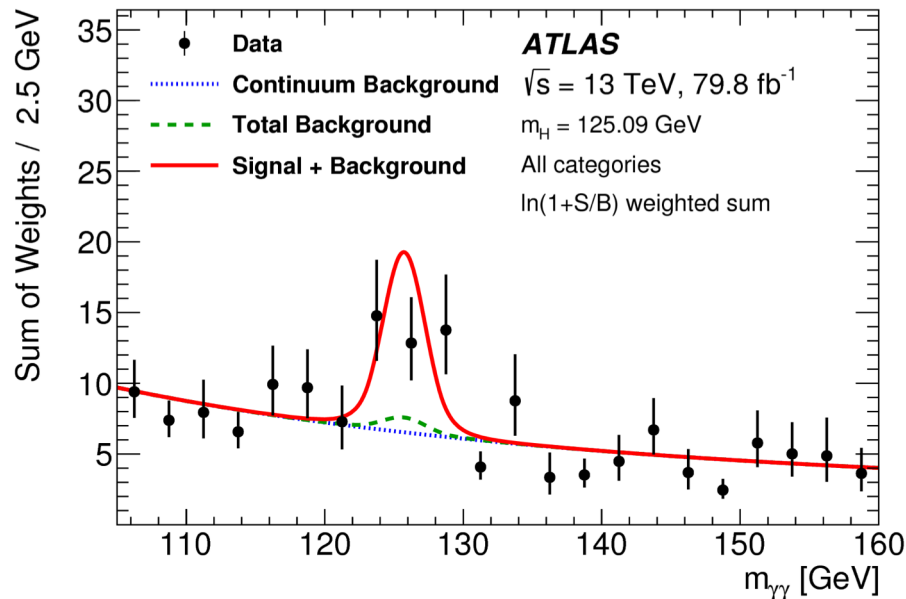
- Last year: **First observation of ttH!**
(first by CMS, then ATLAS; similar strategies, concentrating on ATLAS here)
- Combination of multiple channels:
 - Higgs decay to $b\bar{b}$, WW^* , $\tau^+\tau^-$, $\gamma\gamma$, ZZ^*
 - Hadronic and/or leptonic top decays used



[Phys. Lett. B 784 \(2018\) 173](#)

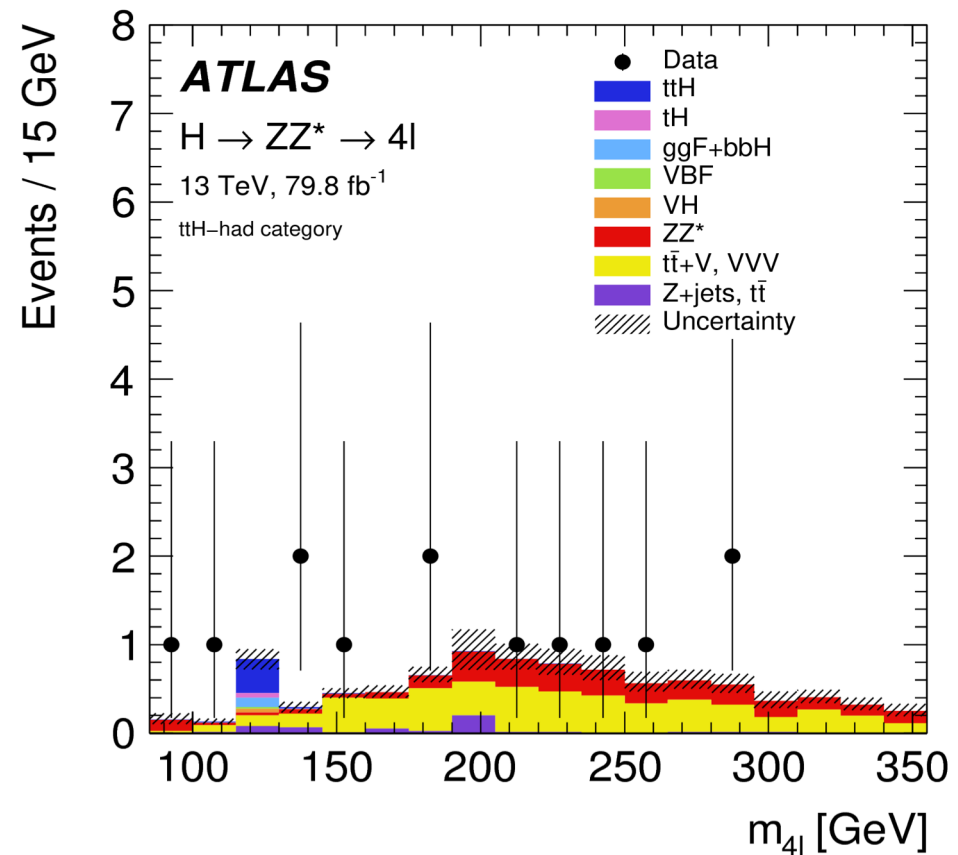
Diphoton Channel

- Define two regions: hadronic top decays or events with at least one charged lepton
 - $m_{\gamma\gamma}$: has to be between 105 and 160 GeV
- For each region: train **BDTs**



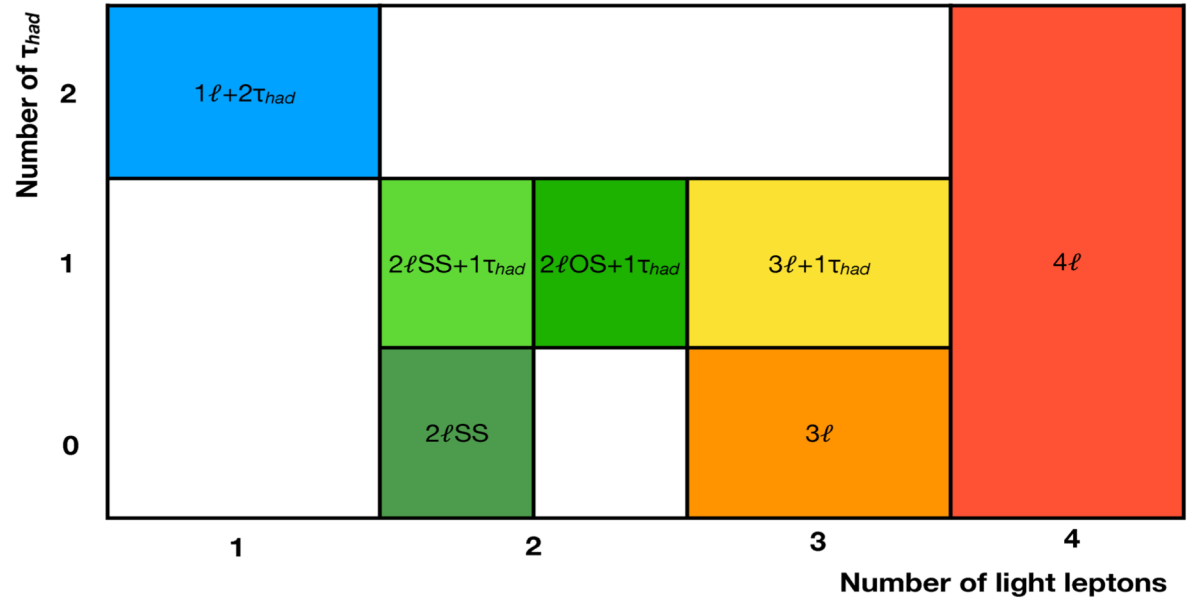
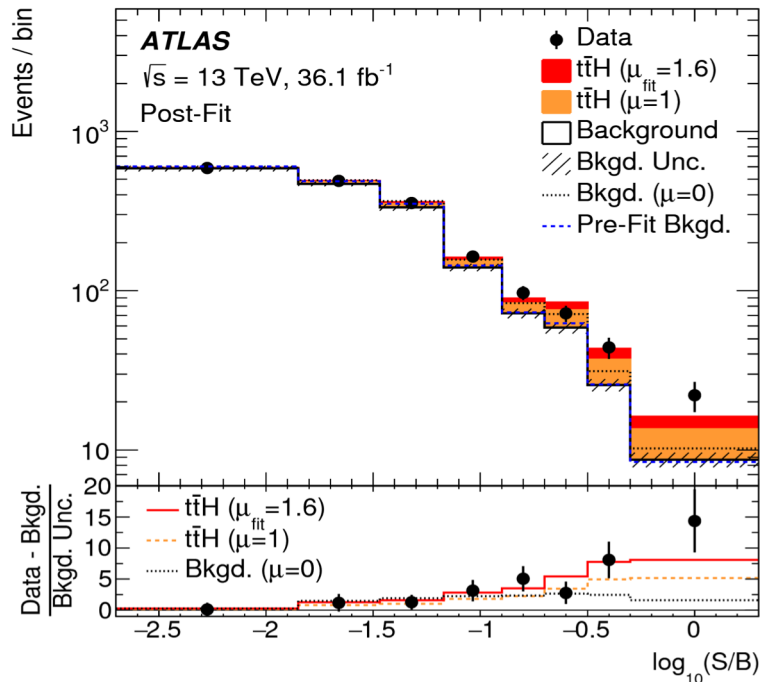
ZZ Channel

- Use events with at least 4 isolated charged leptons
 - Two regions: hadronic (both tops decay hadronically) and leptonic (at least one top decays leptonically)
 - BDT used on hadronic region



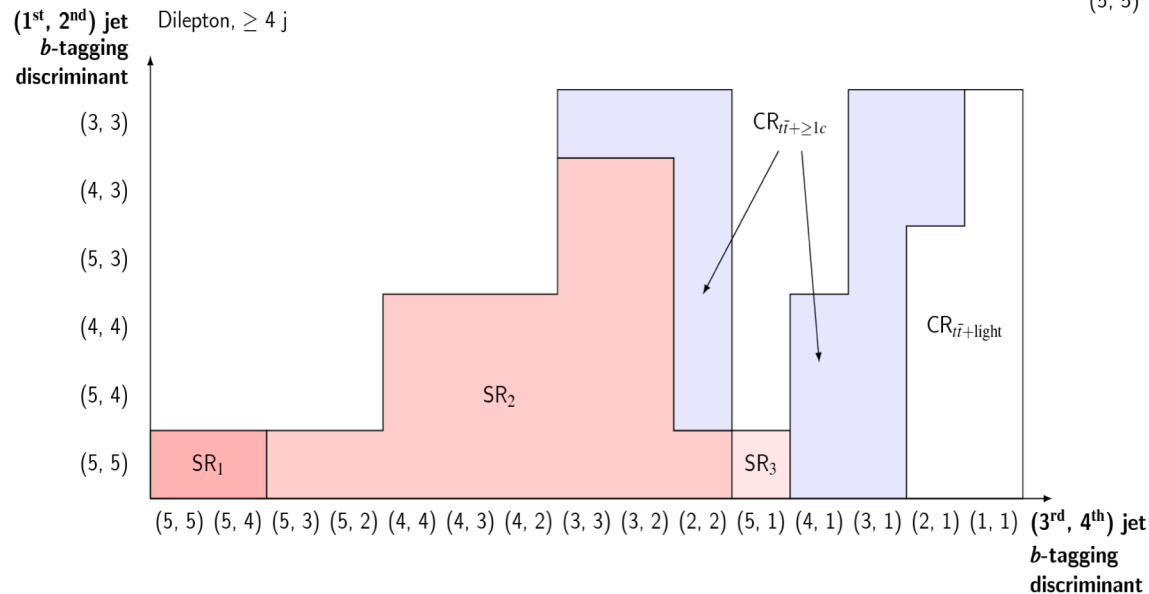
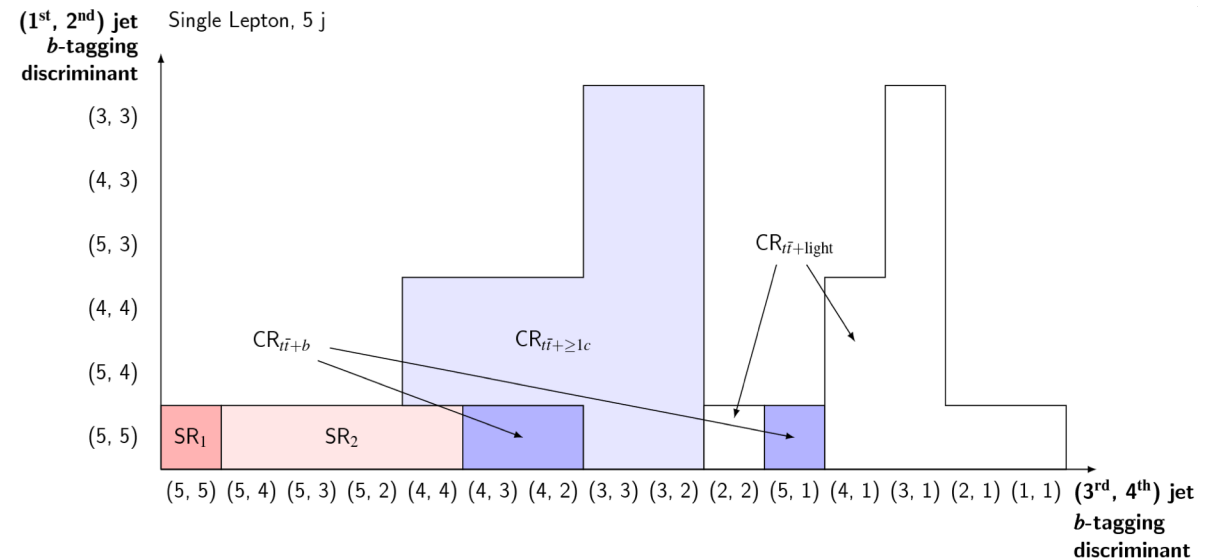
Multilepton Channel

- Includes $H \rightarrow WW$ (& ZZ) and $H \rightarrow \tau\tau$ decays
- Many channels considered
 - Some use BDTs



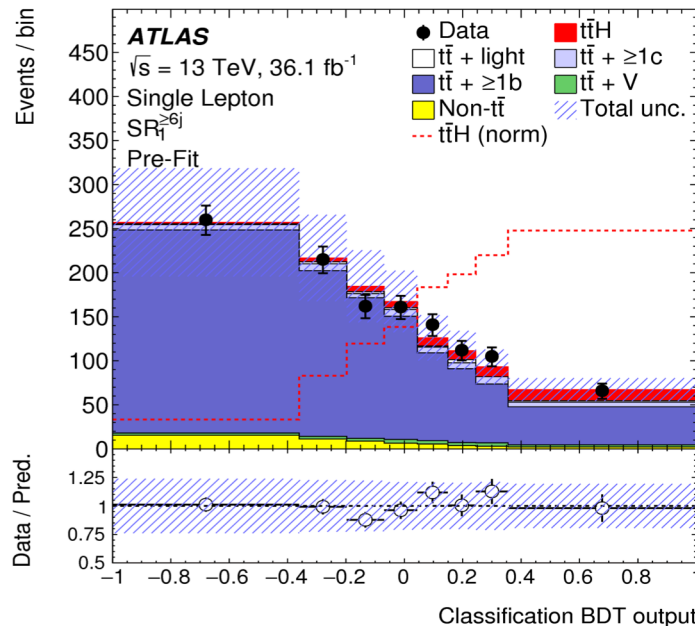
$H \rightarrow b\bar{b}$ Channel

- Semileptonic and dileptonic channels considered
 - Separation in many different **control and signal regions**
- Very challenging analysis
 - Modeling of background $t\bar{t}b\bar{b}$



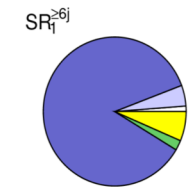
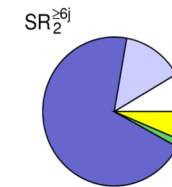
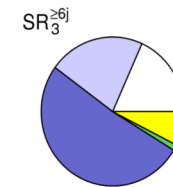
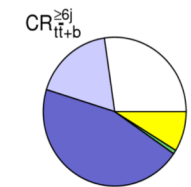
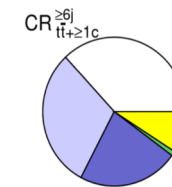
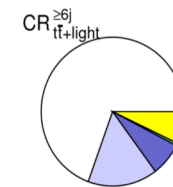
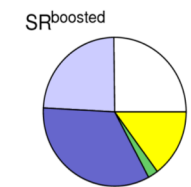
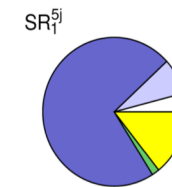
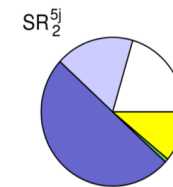
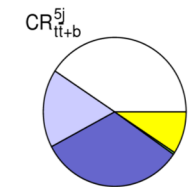
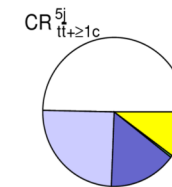
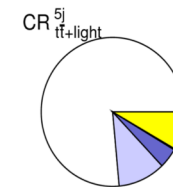
Semileptonic

- BDTs used enhancing significance
 - Reconstruction of event done with "**reconstruction BDT**"
 - access to variables using full events
- Fits including control regions
 - improves control over backgrounds



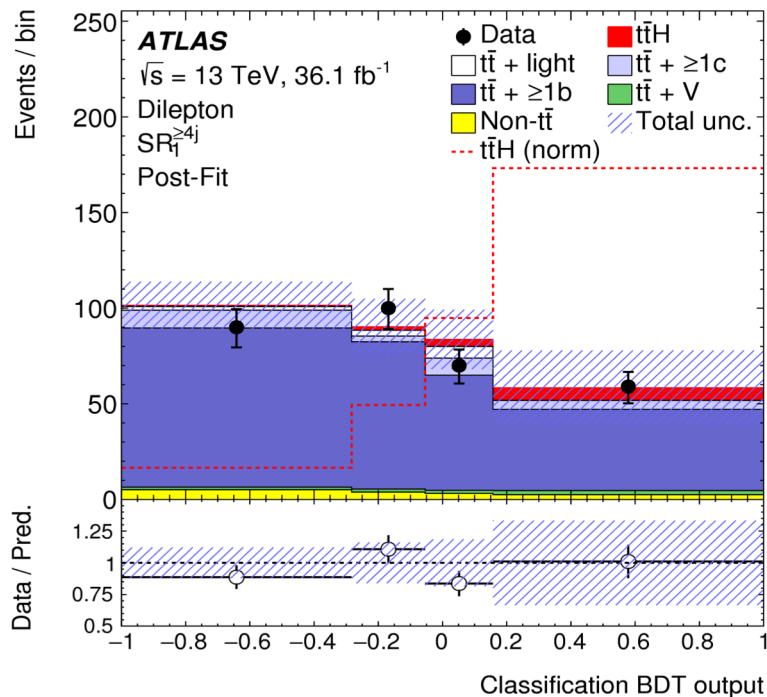
ATLAS
 $\sqrt{s} = 13 \text{ TeV}$
Single Lepton

□ $t\bar{t} + \text{light}$ □ $t\bar{t} + \geq 1c$ ■ $t\bar{t} + \geq 1b$
 ■ $t\bar{t} + V$ ■ Non- $t\bar{t}$



Dileptonic

- Similar strategy as in semileptonic channel
 - Reconstruction of full event information more challenging due to two neutrinos

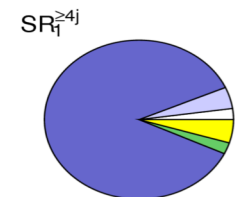
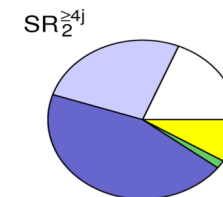
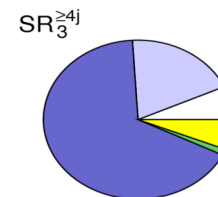
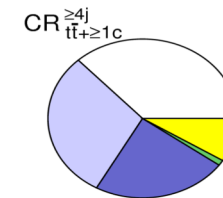
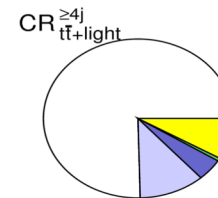
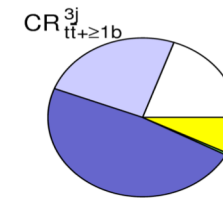
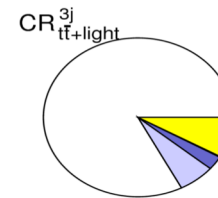


ATLAS

$\sqrt{s} = 13 \text{ TeV}$

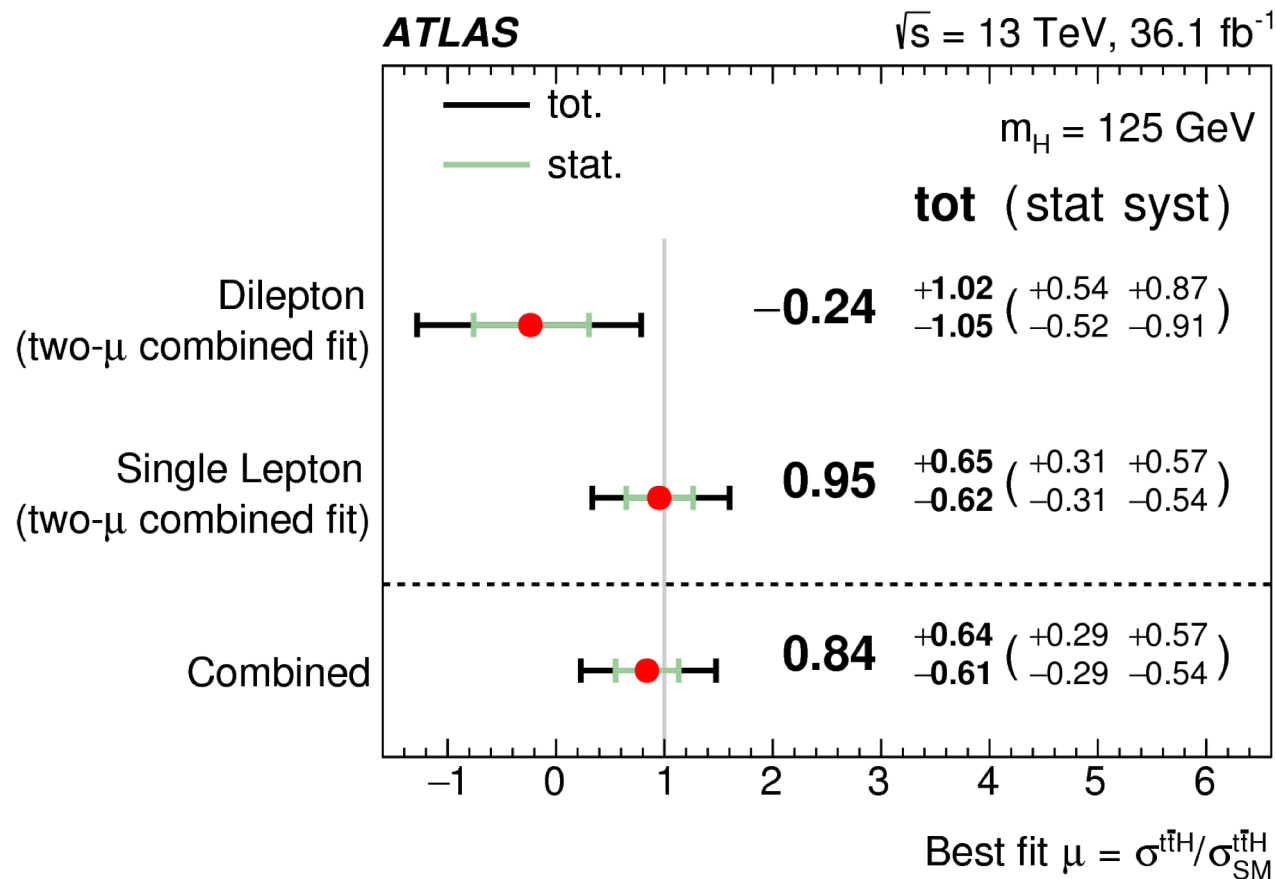
Dilepton

$t\bar{t} + \text{light}$ $t\bar{t} + \geq 1c$ $t\bar{t} + \geq 1b$
 $t\bar{t} + V$ Non- $t\bar{t}$



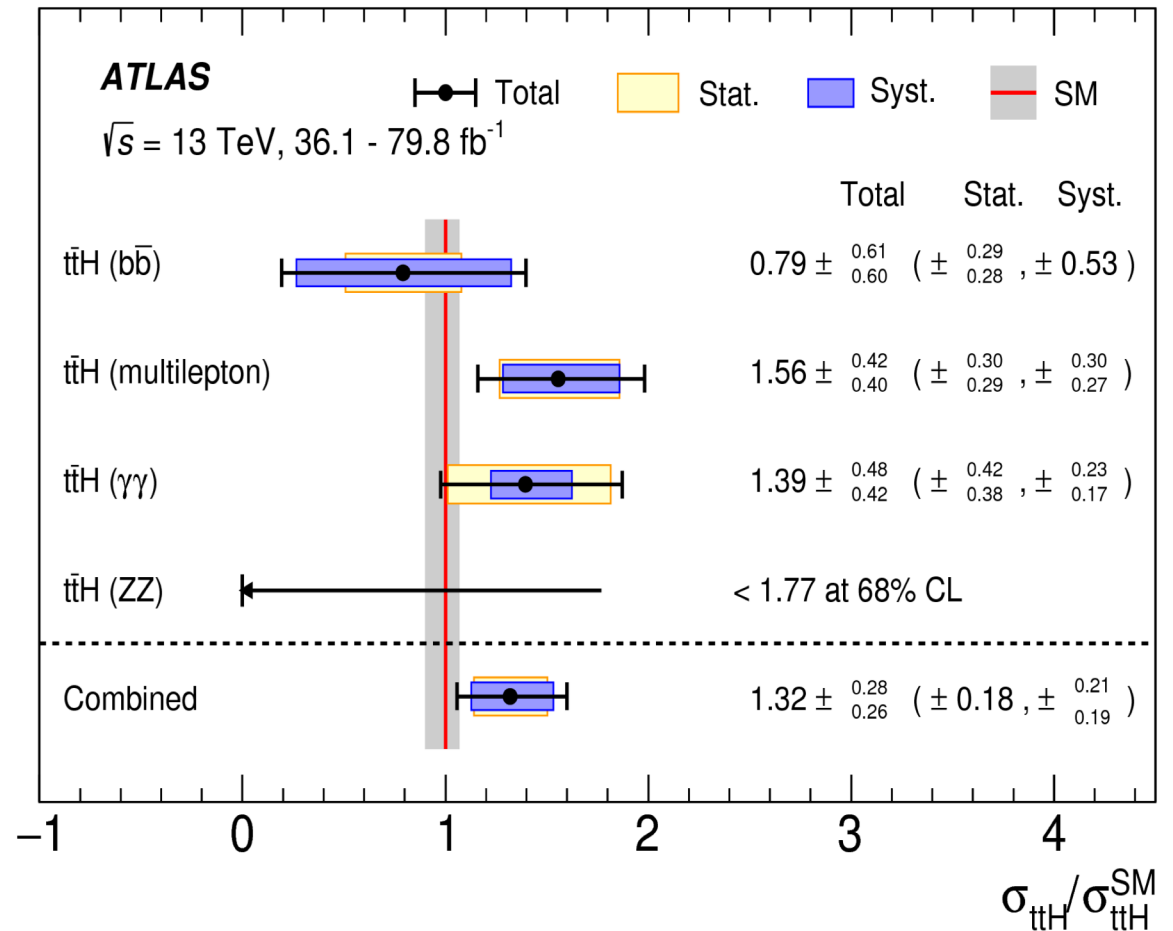
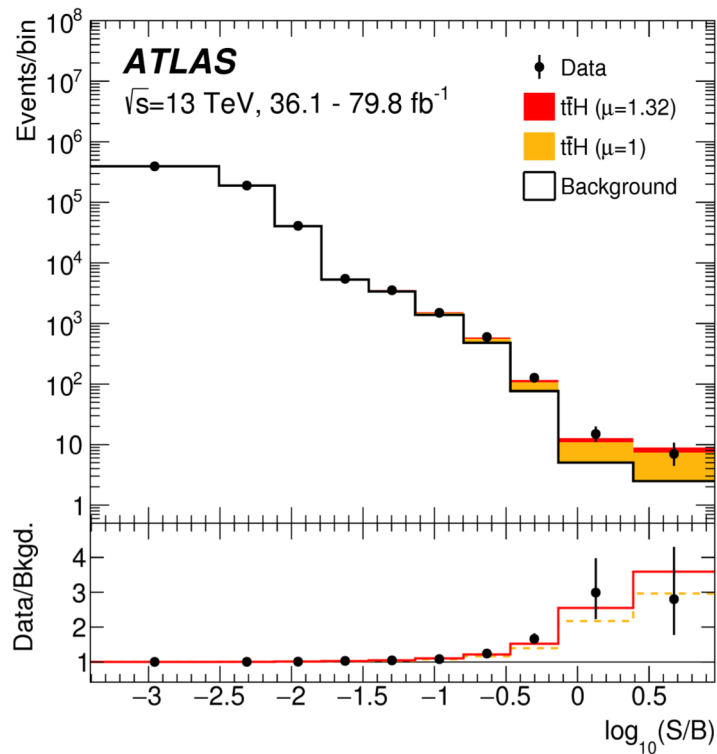
$t\bar{t}H, H \rightarrow b\bar{b}$ Results

- Results already dominated by systematic uncertainties
→ background modeling of $t\bar{t}b\bar{b}$ a main factor



Combination

- Combination of all channels: **Observation of $t\bar{t}H$!**
 - Observed significance of 5.8σ



Summary

- Top Quark Physics: Probing the heaviest known elementary particle!
 - Jet pull: accessing colour-flow information between jets
→ information on **QCD colour-nature** of mother particle
 - Precision measurement of spin correlations
 - probing **the full top production and decay chain ever more precise**
→ still an open riddle where the deviation from prediction comes from
 - Top-Higgs: **observation of ttH**
→ new era of exploring the connection between heaviest elementary particles
- Everything compatible with SM so far
- Tops were, are and stay awesome
→ much to learn about the SM and beyond

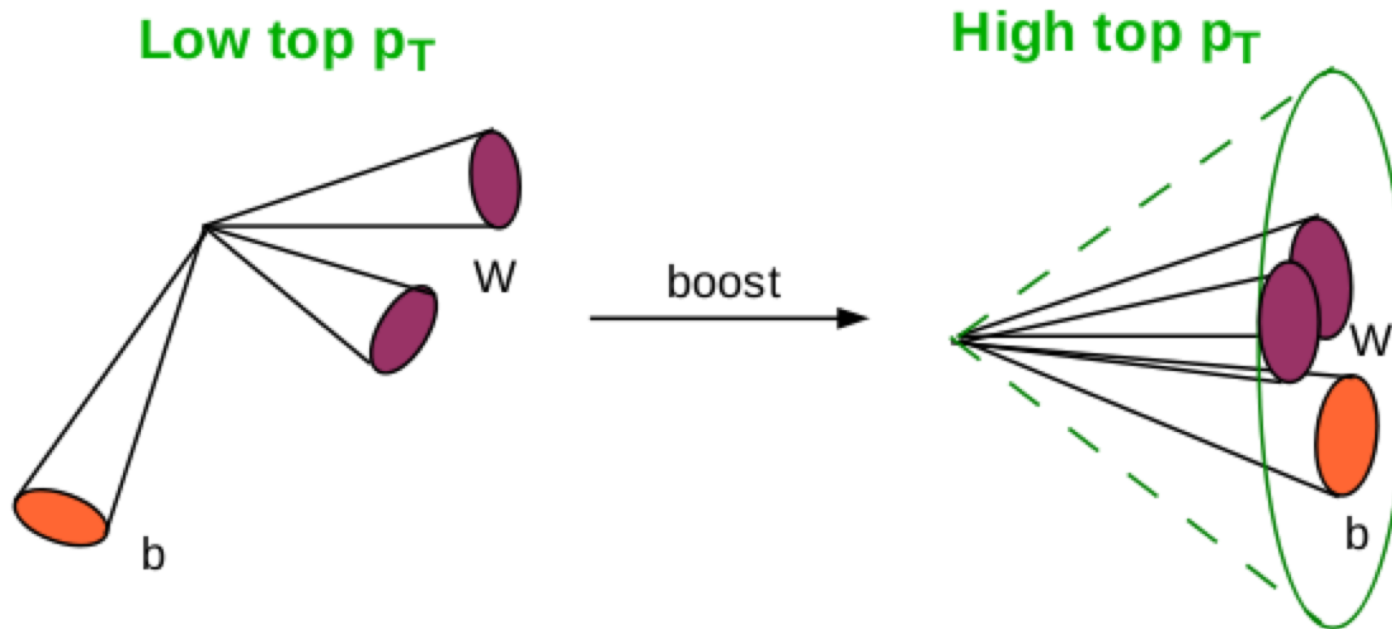


Backup

Boosting algorithms

Boosting algorithms important

- ◆ Higher collision energy $\rightarrow$ more events can be boosted
- ◆ Production of heavy particles $\rightarrow$ decay products can be boosted $\rightarrow$ results in boosted regimes



Colour Flow: Systematics

$\Delta\theta_P (j_1^W, j_2^W) [\%]$	$\theta_P (j_1^W, j_2^W)$			
	0.0 – 0.21	0.21 – 0.48	0.48 – 0.78	0.78 – 1.0
Hadronisation	0.63	0.22	0.27	0.09
Generator	0.37	0.24	0.50	0.06
Colour Reconnection	0.11	0.26	0.03	0.53
b -Tagging	0.35	0.12	0.20	0.31
Non-Closure	0.25	0.07	0.08	0.30
ISR / FSR	0.32	0.12	0.15	0.01
Other	0.25	0.20	0.11	0.18
JER	0.12	0.13	0.21	0.03
JES	0.13	0.06	0.13	0.07
Tracks	0.09	0.04	0.05	0.07
Syst.	0.97	0.52	0.68	0.72
Stat.	0.22	0.18	0.17	0.26
Total	0.99	0.55	0.71	0.76

Spin Correlations: Systematics

Table 5: Summary table of the effect of experimental systematic uncertainties on the f_{SM} extraction. Uncertainties which are smaller than the precision shown are included in the totals and the f_{SM} significance calculations.

Systematic	Inclusive	$m_{t\bar{t}}$ range [GeV]			
		$m_{t\bar{t}} < 450$	$450 \leq m_{t\bar{t}} < 550$	$550 \leq m_{t\bar{t}} < 800$	$m_{t\bar{t}} \geq 800$
Matrix element	± 0.006	± 0.11	± 0.064	± 0.01	± 0.3
Parton shower and hadronisation	± 0.010	± 0.02	± 0.005	± 0.01	± 1.4
Radiation and scale settings	± 0.055	± 0.05	± 0.061	± 0.23	< 0.1
PDF	± 0.002	< 0.01	± 0.003	± 0.01	< 0.1
Background modelling	± 0.009	± 0.01	$+0.014$ -0.015	± 0.01	± 0.1
Lepton ID and reconstruction	± 0.008	± 0.01	$+0.030$ -0.036	$+0.03$ -0.10	$+0.5$ -0.2
b -tagging	$+0.004$ -0.003	± 0.01	± 0.025	$+0.04$ -0.02	$+0.1$ -0.2
Jet ID and reconstruction	$+0.014$ -0.017	$+0.02$ -0.05	$+0.076$ -0.093	$+0.17$ -0.26	$+1.7$ -0.6
$E_{\text{T}}^{\text{miss}}$ reconstruction	< 0.001	$+0.01$ -0.02	$+0.042$ -0.034	$+0.12$ -0.14	$+0.9$ -0.7
Pile-up effects	$+0.013$ -0.010	< 0.01	$+0.015$ -0.019	$+0.07$ -0.04	$+0.2$ -0.4
Luminosity	± 0.001	< 0.01	$+0.002$ -0.000	< 0.01	< 0.1
MC statistical uncertainty	± 0.005	< 0.01	± 0.007	± 0.03	± 0.05
Total systematics	± 0.061	$+0.12$ -0.13	$+0.13$ -0.14	$+0.31$ -0.41	$+2.5$ -1.7